

**Energy Research and Development Division
FINAL PROJECT REPORT**

**ENERGY INNOVATIONS SMALL
GRANT PROGRAM: 2007
INDEPENDENT ASSESSMENT
REPORTS**

Prepared for: California Energy Commission
Prepared by: San Diego State Research Foundation



**SAN DIEGO STATE
UNIVERSITY**

Research Foundation

Science ♦ Service ♦ Solutions

JULY 2007
CEC-500-2013-029

Prepared by:

Primary Author:

Rob Queen
Program Administrator

San Diego State Research Foundation
5250 Campanile Drive,
San Diego, CA 92182-1858
(619) 594-1900

Contract Number: 500-98-014

Prepared for:

California Energy Commission

Raquel E. Kravitz
Contract Manager

Fernando Pina
Office Manager
Energy Efficiency Research Office

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Robert P. Oglesby
Executive Director

DISCLAIMER

This report was prepared as the result of work sponsored by the California Energy Commission. It does not necessarily represent the views of the Energy Commission, its employees or the State of California. The Energy Commission, the State of California, its employees, contractors and subcontractors make no warranty, express or implied, and assume no legal liability for the information in this report; nor does any party represent that the uses of this information will not infringe upon privately owned rights. This report has not been approved or disapproved by the California Energy Commission nor has the California Energy Commission passed upon the accuracy or adequacy of the information in this report.

PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The Energy Research and Development Division strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

Energy Research and Development Division funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Energy Innovations Small Grant Program: 2007 Independent Assessment Reports is the final report for the Energy Innovations Small Grant Program (contract number 500-98-014) conducted by San Diego State University Research Foundation. The information from this project contributes to Energy Research and Development Division's RD&D Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

The California Energy Commission has been conducting the Public Interest Energy Research (PIER) program through competitive solicitations to advance science or technology in each of the seven PIER program areas to benefit California ratepayers since 1997. In addition, the Energy Commission has also funded and managed the Energy Innovations Small Grant (EISG) Program since 1998. The role of the EISG program is to advance research into new and innovative energy concepts and technologies whose feasibility is not yet sufficiently established to meet traditional research and development (R&D) funding requirements.

The Energy Innovations Small Grant (EISG) program supports early-phase development of promising new energy technology concept. This category of projects is not covered by PIER general solicitations that focus primarily on development of established concepts. Qualifying EISG projects address one of the defined PIER RD&D areas. If the feasibility of an innovative energy concept is proven through the EISG project work, then traditional R&D funding may become available to further develop the project.

Independent Assessment Reports (IARs) are written at the completion of every EISG grant project. These reports outline the objectives of the project, discuss the successes and failures, and offer recommendations for potential future work. This report presents a collection of 25 independent assessment reports for EISG grant projects awarded during 2007.

Keywords: Ratepayer, California Energy Commission, Energy Innovations Small Grant, EISG, Independent Assessment Report, IAR, Public Interest Energy Research, PIER RD&D, electricity, natural gas, transportation, research, energy technology concepts, project, market, outcomes, conclusions, benefits

Please use the following citation for this report:

Queen, Robert. San Diego State University Research Foundation. 2007. *Energy Innovations Small Grant Program: 2007 Independent Assessment Reports*. California Energy Commission. Publication number: CEC-500-2013-029.

TABLE OF CONTENTS

PREFACE	i
ABSTRACT	ii
TABLE OF CONTENTS.....	iii
LIST OF FIGURES	xi
List of Tables.....	xii
EXECUTIVE SUMMARY	1
CHAPTER 1:.....	3
Introduction	3
CHAPTER 2:.....	5
2007 Independent Assessment Reports	5
2.1 Novel Heat Transfer Fluid for Heating, Ventilation, and Air Conditioning (HVAC), and Microelectronics Applications	5
2.1.1 Abstract.....	5
2.1.2 Introduction	5
2.1.3 Objectives	7
2.1.4 Outcomes.....	8
2.1.5 Conclusions.....	9
2.1.6 Recommendations.....	10
2.1.7 Benefits to California	10
2.1.8 Technology Transition Assessment.....	11
2.2 Novel Solid Oxide Fuel Cell Anodes for Use with Coal and Biomass Derived Syngas 12	
2.2.1 Abstract.....	12
2.2.2 Introduction	12
2.2.3 Objectives	15
2.2.4 Outcomes.....	16
2.2.5 Conclusions.....	17
2.2.6 Recommendations.....	18

2.2.7	Benefits to California	18
2.2.8	Technology Transition Assessment.....	19
2.3	Thermochemical Processes Platforms to Utilize Crude Glycerin for Hydrogen Production and Electricity Generation.....	20
2.3.1	Abstract.....	20
2.3.2	Introduction	20
2.3.3	Objectives	21
2.3.4	Outcomes.....	22
2.3.5	Conclusions.....	22
2.3.6	Recommendations.....	22
2.3.7	Benefits to California	23
2.3.8	Technology Transition Assessment.....	24
2.4	Novel Cogeneration Process for Wastewater Treatment Plant Operations	25
2.4.1	Abstract.....	25
2.4.2	Introduction	25
2.4.3	Objectives	27
2.4.4	Outcomes.....	28
2.4.5	Conclusions.....	29
2.4.6	Recommendations.....	29
2.4.7	Benefits to California	29
2.4.8	Technology Transition Assessment.....	30
2.5	Air Independent Internal Oxidation Steam Generator	31
2.5.1	Abstract.....	31
2.5.2	Introduction	31
2.5.3	Objectives	32
2.5.4	Outcomes.....	33
2.5.5	Conclusions.....	34
2.5.6	Recommendations.....	34
2.5.7	Benefits to California	35

2.5.8	Technology Transition Assessment.....	35
2.6	Energy Storage for Grid and Renewable Sources.....	36
2.6.1	Abstract.....	36
2.6.2	Introduction	37
2.6.3	Objectives	39
2.6.4	Outcomes.....	39
2.6.5	Conclusions.....	40
2.6.6	Recommendations.....	40
2.6.7	Benefits to California	41
2.6.8	Technology Transition Assessment.....	42
2.7	Fault Location in Power Distribution System with Penetration of Distributed Energy Resources.....	43
2.7.1	Abstract.....	43
2.7.2	Introduction	43
2.7.3	Objectives	44
2.7.4	Outcomes.....	45
2.7.5	Conclusions.....	45
2.7.6	Recommendations.....	46
2.7.7	Benefits to California	46
2.7.8	Technology Transition Assessment.....	47
2.8	Microwave Induced Reaction of NO _x and H ₂ S in Dairy Digester Reciprocating Engines	48
2.8.1	Abstract.....	48
2.8.2	Introduction	48
2.8.3	Objectives	50
2.8.4	Outcomes.....	50
2.8.5	Conclusions.....	51
2.8.6	Recommendations.....	52
2.8.7	Benefits to California	52

2.8.8	Technology Transition Assessment.....	53
2.9	Novel Adaptation of Three Way Catalyst for NOx Reduction in Exhaust of Landfill Gas Engines.....	54
2.9.1	Abstract.....	54
2.9.2	Introduction	54
2.9.3	Objectives	55
2.9.4	Outcomes.....	56
2.9.5	Conclusions.....	56
2.9.6	Recommendations.....	57
2.9.7	Benefits to California	58
2.9.8	Technology Transition Assessment.....	58
2.10	Pomace and Woody Biomass for Renewable Biomass Power: Technical and Economic Feasibility	59
2.10.1	Abstract.....	59
2.10.2	Introduction	60
2.10.3	Objectives	62
2.10.4	Outcomes.....	63
2.10.5	Conclusions.....	64
2.10.6	Recommendations.....	66
2.10.7	Benefits to California	67
2.10.8	Technology Transition Assessment.....	67
2.11	Biogas Generation from Algae Biomass Harvested at Wastewater Treatment Facilities 68	
2.11.1	Abstract.....	68
2.11.2	Introduction	68
2.11.3	Objectives	69
2.11.4	Outcomes.....	70
2.11.5	Conclusions.....	71
2.11.6	Recommendations.....	72

2.11.7	Benefits to California	72
2.11.8	Technology Transition Assessment.....	73
2.12	A Reliable Low Cost Power Electronics Interface for Renewable Energy Systems Using a Single DSP Controller.....	74
2.12.1	Abstract.....	74
2.12.2	Introduction	74
2.12.3	Objectives	76
2.12.4	Outcomes.....	76
2.12.5	Conclusions.....	76
2.12.6	Recommendations.....	77
2.12.7	Benefits to California	77
2.12.8	Technology Transition Assessment.....	78
2.13	Aquatic Biomass to Fuel.....	79
2.13.1	Abstract.....	79
2.13.2	Introduction	79
2.13.3	Objectives	80
2.13.4	Outcomes.....	81
2.13.5	Conclusions.....	82
2.13.6	Recommendations.....	82
2.13.7	Benefits to California	83
2.13.8	Technology Transition Assessment.....	83
2.14	Wind Turbine Load Limiting Algorithm Verification Testing.....	84
2.14.1	Abstract.....	84
2.14.2	Introduction	85
2.14.3	Objectives	86
2.14.4	Outcomes.....	87
2.14.5	Conclusions.....	88
2.14.6	Recommendations.....	89
2.14.7	Benefits to California	89

2.14.8	Technology Transition Assessment.....	90
2.15	Low Cost Hydrogen Sulfide Reduction in Biogas Energy Systems.....	91
2.15.1	Abstract.....	91
2.15.2	Introduction	91
2.15.3	Objectives	92
2.15.4	Outcomes.....	93
2.15.5	Conclusions.....	94
2.15.6	Recommendations.....	95
2.15.7	Benefits to California	95
2.15.8	Technology Transition Assessment.....	96
2.16	Charge Air Chiller.....	97
2.16.1	Abstract.....	97
2.16.2	Introduction	98
2.16.3	Objectives	100
2.16.4	Outcomes.....	100
2.16.5	Conclusions.....	101
2.16.6	Recommendations.....	102
2.16.7	Benefits to California	102
2.16.8	Technology Transition Assessment.....	103
2.17	A New Approach to CO2 Capture	104
2.17.1	Abstract.....	104
2.17.2	Introduction	104
2.17.3	Objectives	105
2.17.4	Outcomes.....	106
2.17.5	Conclusions.....	106
2.17.6	Recommendations.....	107
2.17.7	Benefits to California	108
2.17.8	Technology Transition Assessment.....	108

2.18	Demand Response Load Shedding System for Lighting.....	109
2.18.1	Abstract.....	109
2.18.2	Introduction	110
2.18.3	Objectives	111
2.18.4	Outcomes.....	111
2.18.5	Conclusions.....	112
2.18.6	Recommendations.....	113
2.18.7	Benefits to California	113
2.19	Tandem Organic Solar Cell Using CNT and Mixed Quantum Dots	115
2.19.1	Abstract.....	115
2.19.2	Introduction	115
2.19.3	Objectives	116
2.19.4	Outcomes.....	116
2.19.5	Conclusions.....	117
2.19.6	Recommendations.....	117
2.19.7	Benefits to California	118
2.20	High G-load Combustor for Microturbines	119
2.20.1	Abstract.....	119
2.20.2	Introduction	120
2.20.3	Objectives	122
2.20.4	Outcomes.....	123
2.20.5	Conclusions.....	123
2.20.6	Recommendations.....	124
2.20.7	Benefits to California	124
2.21	Novel Heat Exchanger Fin Surface Design for Improved Condensate Management..	126
2.21.1	Abstract.....	126
2.21.2	Introduction	126
2.21.3	Objectives	128

2.21.4	Outcomes.....	129
2.21.5	Conclusions.....	131
2.21.6	Recommendations.....	132
2.21.7	Benefits to California	132
2.21.8	Technology Transition Assessment.....	133
2.22	Algae Biomass Gasification	133
2.22.1	Abstract.....	133
2.22.2	Introduction	134
2.22.3	Objectives	135
2.22.4	Outcomes.....	135
2.22.5	Conclusions.....	136
2.22.6	Recommendations.....	136
2.22.7	Benefits to California	136
2.23	Reducing Natural Gas Consumption by Modifying Containers of Water Heaters	138
2.23.1	Abstract.....	138
2.23.2	Introduction	138
2.23.3	Objectives	140
2.23.4	Outcomes.....	140
2.23.5	Conclusions.....	141
2.23.6	Recommendations.....	142
2.23.7	Benefits to California	142
2.23.8	Technology Transition Assessment.....	143
2.24	Low Cost Parabolic Trough.....	144
2.24.1	Abstract.....	144
2.24.2	Introduction	145
2.24.3	Objectives	147
2.24.4	Outcomes.....	148
2.24.5	Conclusions.....	149

2.24.6	Recommendations.....	150
2.24.7	Benefits to California	151
2.24.8	Technology Transition Assessment.....	152
2.25	Production of Syngas from Dairy Manure to Replace Natural Gas	153
2.25.1	Abstract.....	153
2.25.2	Introduction	154
2.25.3	Objectives	156
2.25.4	Outcomes.....	157
2.25.5	Conclusions.....	158
2.25.6	Recommendations.....	158
2.25.6	Benefits to California	159

LIST OF FIGURES

Figure 1:	Schematic Representation of Durability Loop.....	7
Figure 2:	High Resolution Electron Microscope Image Showing Ru Metal Nano-clusters Formed on the Surface of (La,Sr)(Cr,Ru)O ₃ Anode Surface after Exposure to Hydrogen Fuel at 750O C for 45 Hours	15
Figure 3:	A Schematic Diagram of a Fixed Bed Gasifier.....	21
Figure 4:	Schematic of Overall Process	27
Figure 5:	Storage Concept Block Diagram.....	39
Figure 6:	Algorithm to Identify the Faulted Section	44
Figure 7:	Picture of Lab Scale Microwave Reactor System	49
Figure 8:	Multi-Stage Catalytic Converter Exhaust System Test Setup	55
Figure 9:	Renewable Energy Products from Winery Waste.....	61
Figure 10:	Flowstream Diagram of Pretreatment Steps.....	62
Figure 11:	Schematic of a Wastewater Treatment Pond Process Modified to Include Anaerobic Digestion of the Algae	69
Figure 12:	Block Diagram of the Proposed Power Electronics Interface.....	75

Figure 13: Photograph of the DSP Development Board and Connections to Other Parts of the System.....	75
Figure 14: The VPF-AD System.....	80
Figure 15: Logic Diagram for the Load Limiting Algorithm	86
Figure16: CART Results for 25 Numerical Tests	88
Figure 17: Schematic Layout of Digester Air Injection System.....	92
Figure 18: Schematic of Engine with Three Stage Inlet Chiller	100
Figure 19: Schematic Diagram of Carbon Dioxide Separation Setup	105
Figure 20: Scheme to Prepare MWCNTs/PbS QDs and MWCNT/CdS QDs Composites.....	116
Figure 21: Schematic of the High G Load Combustor Concept for Flame Stabilization.....	122
Figure 22: Photograph of a Constructed Coil and Schematic of Relevant Geometry	127
Figure 23: Photo of a Representative Fin Sample Prepared for Coil #3 with SEM Image Showing Underlying Microstructure after Wet Etching.....	127
Figure 24: Process and Instrumentation Diagram for the Gasification of Glucose.....	134
Figure 25: Flowchart Showing the General CAE Approach Adopted Throughout the Project	138
Figure 26: First Baffle Design.....	139
Figure 27: Heat Collection Element (HCE).....	147
Figure 28: Flow Chart of the Proposed Dairy Manure–Wheat Straw to Medium Btu Gas	156

LIST OF TABLES

Table 1.1: 2007 EISG Projects with IARs Included in this Section.....	3
Table 1: H ₂ S-NO-O ₂ Destruction Experimental Data	50
Table 2: Pomace Waste and Power Production Potential as a Function of Capacity	66
Table 3: Performance Level of Each of Three Injection Systems	93
Table 4: Performance Level of Two Covered Lagoon Systems after Extended Run	93
Table 5: Installed Cost for Two Covered Lagoon Air Injection Systems.....	94
Table 6: Estimated Parasitic Load and Operating Costs for Two Covered Lagoon Systems.....	94
Table 7: Comparison of the Various Assessment Methods.....	128

EXECUTIVE SUMMARY

The Energy Innovations Small Grant (EISG) program is a component of the Public Interest Energy Research (PIER) Program managed by the California Energy Commission. The PIER Program benefits California electric and gas ratepayers by funding energy research, development, and demonstration (RD&D) projects that are not adequately provided for by the competitive and regulated energy markets.

The Energy Commission recognizes the need for a program to support the early development of promising new energy technology concepts that are not mature enough to be covered by PIER general solicitations. The Energy Commission has established the EISG program to meet this need.

This report is a compilation of the Individual Assessment Reports (IARs) for grant projects that were awarded in 2007 and that have not been previously published.

All data sources for tables and figures are from the author unless otherwise noted.

CHAPTER 1:

Introduction

Table 1.1: 2007 EISG Projects with IARs Included in this Section

Project	Researcher	EISG Funding
Novel Heat Transfer Fluid for Heating, Ventilation and Air Conditioning (HVAC), and Microelectronics Applications	Texas A&M University	\$93,906
Novel Solid Oxide Fuel Cell Anodes for Use with Coal and Biomass Derived Syngas	Northwestern University	\$94,993
Thermochemical Processes Platforms to Utilize Crude Glycerin for Hydrogen Production and Electricity Generation	University of Arkansas Division of Agriculture	\$ 95,000
Novel Cogeneration Process for Wastewater Treatment Plant Operations	C/e- Solutions, Inc.	\$94,817.13
Air Independent Internal Oxidation Steam Generator	Clean EnGen Group, LLC	\$95,000
Energy Storage for Grid and Renewable Sources	EnStorage Israel Ltd.	\$95,000
Fault Location in Power Distribution System with Penetration of Distributed Energy Resources	Regents of New Mexico State University	\$50,000
Microwave Induced Reaction of NO_x and H₂S in Dairy Digester Reciprocating Engines	CHA Corporation	\$95,000
Novel Adaptation of Three Way Catalyst for NO_x Reduction in Exhaust of Landfill Gas Engines	University of California Berkeley	\$92,500
Pomace and Woody Biomass for Renewable Biomass Power: Technical and Economic Feasibility	Consultant	\$95,000
Biogas Generation from Algae Biomass Harvested at Wastewater Treatment Facilities	California Polytechnic State University Corporation	\$86,000
A Reliable Low Cost Power Electronics Interface for Renewable Energy Systems Using a Single DSP Controller	University of Houston	\$80,975
Aquatic Biomass to Fuel	Michael Cohen	\$70,938
Wind Turbine Load Limiting Algorithm Verification Testing	University of California Davis	\$94,815

Low Cost Hydrogen Sulfide Reduction in Biogas Energy Systems	BioEnergy Solutions, LLC	\$93,896
Charge Air Chiller	Energy Concepts Company, LLC	\$95,000
A New Approach to CO₂ Capture	University of Wyoming	\$88,972
Demand Response Load Shedding System for Lighting	Exergy Controls, LLC	\$94,895
Tandem Organic Solar Cell Using CNT and Mixed Quantum Dots	UC Davis	\$81,438
High G-load Combustor for Microturbines	The Pennsylvania State University	\$95,000
Novel Heat Exchanger Fin Surface Design for Improved Condensate Management	Miami University	\$77,993
Algae Biomass Gasification-NG	QuantumSphere Inc.	\$94,560
Reducing Natural Gas Consumption by Modifying Containers of Water Heaters-NG	Auburn University	\$95,000
Low Cost Parabolic Trough-NG	Randal Perisho	\$55,000
Production of Syngas from Dairy Manure to Replace Natural Gas-NG	University of Arkansas Division of Agriculture Department of Biological & Agricultural Engineering	\$95,000

CHAPTER 2:

2007 Independent Assessment Reports

The Energy Innovations Small Grant (EISG) program awards numerous grants for innovative energy research projects every year. Independent Assessment Reports (IARs) highlight the project outcomes for each of the EISG projects. This chapter includes the IARs from grant projects that were awarded in 2007 that have not previously been published.

2.1 Novel Heat Transfer Fluid for Heating, Ventilation, and Air Conditioning (HVAC), and Microelectronics Applications

Awardee: Texas A&M University

Principal Investigator: Jorge L. Alvarado

2.1.1 Abstract

The goal of this project was to determine the feasibility of using nanoparticles (NPs), multiwall carbon nanotubes (MWCNTs), and microencapsulated phase change materials (MPCM) in heat transfer fluids to increase heat capacity and heat transfer rates by 70 percent and 40 percent, respectively, while reducing pumping energy and heat transfer area significantly. Using deionized water as a control, the researchers explored incremental improvements in thermal properties through the addition of spherical alumina NPs, gelatin encapsulated octadecane MPCMs, MWCNTs, and a blend of MPCMs and MWCNTs. Particle aggregation ultimately proved an insurmountable issue for consideration of NPs as a component in the enhanced fluid. Rather, a solution of 10 percent by weight MPCMs and 1 percent by weight MWCNTs provided the maximum improvement. This slurry provided a thermal conductivity enhancement of 8.11 percent and a maximum heat transfer coefficient enhancement of approximately 25 percent, both significantly lower than the target goals. The improvements in thermal properties came with a slight pressure drop penalty and a significant expense, which rendered the proposed technology applicable only to niche and high-end applications such as the microelectronics industry.

Keywords: Microencapsulated phase change material, nanofluids, carbon nanotubes, heat transfer

2.1.2 Introduction

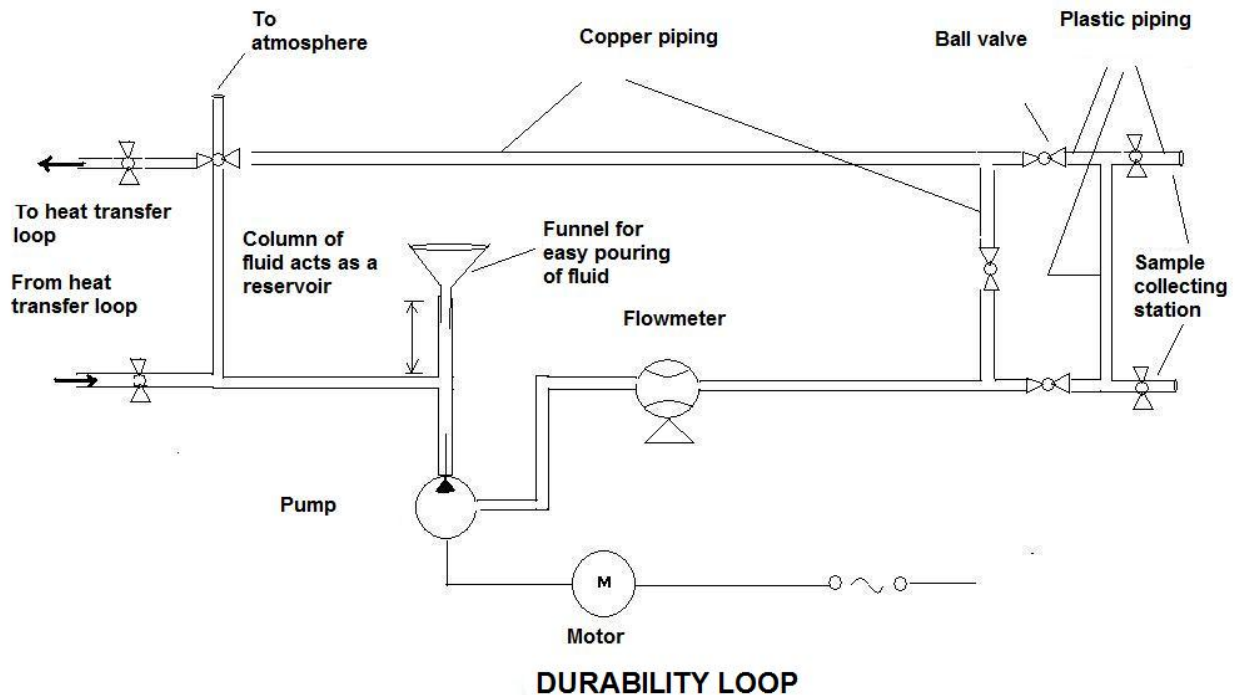
Recent improvements in thermal management and storage have focused on the use of phase change materials (PCMs) to leverage the latent heat storage potential not provided by currently used sensible storage media. This additional storage potential can be used to improve efficiency, reduce the required size, and otherwise enhance the thermal transfer capabilities of heat storage systems. Recently, microencapsulated PCMs (MPCMs) have been developed to increase the heat capacity of thermal systems. However improvements in microelectronics components

resulting in significant increases in computing speed necessitate improvements in heat dissipation capabilities as well. The present study incorporated both MPCMs and high thermal conductivity microparticles to improve both the thermal conductivity and the heat transfer characteristics beyond current technology. The researchers considered and analyzed spherical alumina nanoparticles (NPs), gelatin encapsulated octadecane MPCMs, multiwall carbon nanotubes (MWCNTs), and a blend of MPCMs and MWCNTs in the formulation of a new heat transfer fluid.

The researchers conducted tests using a 10 m durability loop as shown in Figure 1. They prepared slurries using each component listed above. Then they subjected the slurries to repeated cycling through the loop and analyzed them for particle aggregation, MPCM durability, thermal conductivity, viscosity, heat transfer coefficient, and pressure drop through the system. They used laboratory tests and numerical modeling to design an optimal fluid consisting of 10 percent by weight MPCMs and 1 percent by weight MWCNTs to provide maximum improvement. This slurry provided a thermal conductivity enhancement of 8.11 percent and a maximum heat transfer coefficient enhancement of approximately 25 percent, both significantly lower than the target goals.

The proposed heat transfer fluid was intended to allow for the development of smaller heat transfer equipment or to provide the enhanced efficiency required to accommodate advances in microelectronics applications. However the modest improvements in heat transfer characteristics were overshadowed by the significant costs associated with the slurry components. The researchers estimated the proposed fluid could cost between \$200 and \$400 per gallon. Therefore only niche or high-end applications would be able to benefit from the technology. Additionally, the slight pressure drop penalty would result in an increased pumping power requirement for systems using the proposed fluid, rather than an energy savings as envisioned.

Figure 1: Schematic Representation of Durability Loop



2.1.3 Objectives

The goal of this project was to determine the feasibility of using nanoparticles (NPs), multiwall carbon nanotubes (MWCNTs), and microencapsulated phase change materials (MPCM) in heat transfer fluids that could increase heat capacity and heat transfer rates by 70 percent and 40 percent, respectively, while reducing pumping energy and heat transfer area significantly. The researchers established the following project objectives:

1. Verify that MWCNTs have the appropriate length-to-diameter ratio, diameter, and morphology to ensure good heat transport. Verify by dynamic light scattering (DLS) that NPs in heat transfer fluid samples are stable and well dispersed by ensuring the average particle size is 50 nm or less.
2. Verify that heat transfer fluids are stable in the short and long term by recording and comparing light absorbance spectra of each sample.
3. Demonstrate that MWCNTs and NPs can increase the thermal conductivity of water by at least 40 percent.
4. Demonstrate by calorimetry that at least 85 percent of the phase change materials and MWCNTs can be microencapsulated effectively.
5. Demonstrate that the devised heat transfer fluid can increase the heat capacity and heat transfer rate by at least 70 percent and 40 percent, respectively.

6. Demonstrate that the pressure drop for the devised heat transfer fluid is less or equal to water at the same fluid velocity.
7. Demonstrate that the devised heat transfer fluid performs better than water in different heat exchangers under identical conditions and yields greater effectiveness values than water in HVAC and microelectronics applications.

2.1.4 Outcomes

1. The researchers initially dispersed spherical alumina nanoparticles in water to optimize thermal conductivity. However the particle clusters could not be reduced below 125 nm and thermal conductivity enhancement was less than 35. Consequently the researchers tested a variety of MWCNTs ranging in length from 1 to 40 μm and diameter from 10 to 100 nm. The researchers did not discuss the effects of the selected length-to-diameter ratios and their effect on heat transport.
2. The researchers dispersed MWCNTs in deionized water using gum arabic as a surfactant. They then stored the fluid for over one year with no visible sedimentation.
3. The researchers measured transient thermal conductivity using a transient hot wire apparatus. They tested samples from Objective 1 dispersed in deionized water with various mixing times within a closed loop circuit. The maximum thermal conductivity enhancement of 8.475 was achieved using 1.122 percent by weight MWCNTs with a diameter of 60 to 100 nm, a length of 0.5 to 40 μm , and a mixing time of 20 minutes. Researchers then performed viscosity testing of the optimal MWCNTs under varying temperatures.
4. The researchers pumped a 14 percent by weight MPCM slurry continuously through a 10 m closed copper piping loop to test for durability. MPCMs within the slurry consisted of octadecane coated in gelatin. Microcapsules ranged in diameter from 2 to 10 μm with an average diameter of 5 μm . Researchers circulated the slurry through 600 cycles under different flow velocities. The negligible amount of free octadecane observed in the slurry after durability testing under various flow velocities indicated that the MPCM slurry was extremely durable. Testing reported in the literature performed for over 2000 cycles confirmed the results of the research.
5. The researchers modified the 10 m closed loop to include a heat transfer section, data logger, and heat exchanger. Fluids tested included deionized water as a control, 7 percent by weight MPCM slurry (Sample 1), 11 percent by weight MPCM slurry (Sample 2), 1.1 percent by weight MWCNT slurry (Sample 3), and a mixture of 11 percent by weight MPCM and 1.1 percent by weight MWCNT (Sample 4). The researchers did not present results for the heat capacity, but they noted a 40 percent enhancement for the MPCM slurry. The heat transfer coefficient increased by a maximum of approximately 20 percent, 40 percent, and 25 percent for Samples 1, 2, and 3, respectively. Results reported from the literature indicated the combination of MPCM and MWCNT could increase the heat transfer coefficient by a maximum of approximately 9 percent, but could also degrade performance, depending on the heat flux value and flow rate. Note

that the Program Administrator estimated the heat transfer coefficient increases using Figures 20 through 27 of the Final Report.

6. The researchers used three pressure transducers at different locations along the closed heat transfer circuit to measure the pressure drop of water (control), 11 percent by weight MPCM slurry, 0.5 percent by weight MWCNT slurry, 1.1 percent by weight MWCNT slurry, and a mixture of 11 percent by weight MPCM and 1.1 percent by weight MWCNT, while varying heat flux and flow rate. In all cases, the pressure drop of the tested fluid was higher than the control. The pressure drop of the MPCM and MWCNT blend was approximately three times that of water at all flow rates tested.
7. Researchers considered a concentric tube heat exchanger for a parametric numerical modeling study. The optimal blended fluid consisted of 10 percent by weight MPCMs and 1 percent by weight MWCNTs. Results indicated 0.05 L/s of heat transfer fluid flow was required to generate 1 kW. The researchers presented graphical results for the fluid at various states of MPCM phase change. However they did not give a comparison for water as the control. Analysis of alternate heat exchanger configurations were in progress, but not included in the Final Report. The researchers did not present effectiveness comparisons in HVAC and microelectronics applications in the study.

2.1.5 Conclusions

1. The researchers were not successful in dispersing NPs in a fluid with an average particle size of 50 nm or less. Rather, they substituted MWCNTs with varying lengths and diameters. They used wet transmission electron microscopy (TEM) to qualitatively assess dispersion of the MWCNTs within the fluid. The researchers noted that a greater ultrasonic processing time resulted in a decrease of the nanotube aspect ratio. However they did not discuss the implications.
2. The researchers were successful in preparing a stable heat transfer fluid. Although they noted that no sedimentation was observed after one year, they did not include images of the light absorbance spectra study in their report.
3. The researchers were not successful in achieving a minimum thermal conductivity increase of 40 percent. The maximum enhancement achieved was 8.47 percent.
4. The researchers were successful in demonstrating the durability of MPCMs. They detected only negligible free octadecane after 600 cycles through a 10 m closed circuit at various flow rates.
5. The researchers were not successful in devising a heat transfer fluid with a heat capacity increase of 70 percent and a heat transfer rate increase of 40 percent. They obtained research results of slightly more than half the targeted goal.
6. The researchers were not successful in demonstrating that the pressure drop for the devised heat transfer fluid would be less than or equal to water at the same fluid velocity. The MPCM slurry exhibited the lowest pressure drop of all fluids tested, and the MWCNT exhibited the greatest pressure drop. Addition of MPCM to the MWCNT

slurry improved the performance due to the shear thinning behavior of the blend. The researchers noted that the blended fluid should nevertheless be able to find use in applications where the pressure drop penalty was not a significant concern.

7. The researchers were not successful in demonstrating that the devised heat transfer fluid performs better than water in different heat exchangers under identical conditions and yields greater effectiveness values than water in HVAC and microelectronics applications. They investigated only one configuration as part of the research. They noted that work on alternate configurations was in progress. Graphical results presented do not readily support the researchers' conclusion that the heat transfer fluid leads to "enhancement in heat transfer performance of about 15 percent or more in most cases."

2.1.6 Recommendations

The researchers were able to demonstrate only marginal improvement (8 percent) in thermal conductivity by incorporation of MPCMs and MWCNTs into deionized water. However this improvement came at significant expense and a slight pressure drop penalty. A preliminary analysis indicated that the proposed fluid would cost between \$200 and \$400 per gallon. Consequently this technology could find applicability only in niche or high end applications such as the microelectronics industry. Broad applicability to other industries, including residential applications, would require a significant improvement in the cost/benefit ratio by reducing production costs of components by at least a factor of 10 and exploring alternate components that would provide for thermal capacity improvements approaching the original project goal. As part of continued development of this technology, the Program Administrator recommends that the following tasks be completed:

1. Continue exploring alternative MPCMs and MWCNTs for improved thermal performance characteristics.
2. Investigate alternative encapsulation technologies or methods for inclusion of PCMs in the heat exchange system.
3. Clarify and enhance the comparison proposed as part of Objective 7. Include results of alternative heat exchanger configurations.

2.1.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. The use of a solar thermal storage system could lead to adoption of solar energy for water heating and air conditioning in residential and commercial applications. The researchers estimated a domestic hot water system could save up to 30 percent of the total energy in a home or approximately 4 kWh/ft² per year. This translates into annual savings of more than \$100M for California ratepayers. This would also result in a carbon dioxide emission reduction of approximately 1M metric tons annually.

2.1.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.1.8.1 Marketing/Connection to the Market

A formal market analysis has not been conducted. However the expense of the technology limits its applicability to niche or high end industries such as microelectronics.

2.1.8.2 Engineering/Technical

Material cost is the primary technical barrier. The researchers are working with suppliers to identify alternate technologies and components for the heat transfer fluid.

2.1.8.3 Legal/Contractual

The researchers have performed a patent search and have filed a provisional patent for the technology.

2.1.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

MWCNTs pose a safety risk in dry form and need to be handled with care. Although the MPCMs proved to be durable, health and safety concerns related to the PCM should be investigated. Environmental, safety, risk assessment/quality plans have not yet been prepared.

2.1.8.5 Production Readiness/Commercialization

The researchers plan to pursue commercialization and have identified potential commercialization partners, but the technology is not sufficiently cost effective to be market ready. They are pursuing commercialization under a Federal (NSF-STTR) grant and plan to submit a Department of Defense (ESTCP) proposal to test fluids in the field and eventually to commercialize the devised heat transfer fluid.

2.2 Novel Solid Oxide Fuel Cell Anodes for Use with Coal and Biomass Derived Syngas

Awardee: Northwestern University

Principal Investigator: Scott A. Barnett

2.2.1 Abstract

Coal and biomass are plentiful domestic energy sources for economical electricity generation. However when combusted in air, both produce a carbon dioxide (CO₂) effluent diluted with atmospheric nitrogen (N₂). The nitrogen must be removed from the CO₂ before it can be economically captured and sequestered. A solid oxide fuel cell (SOFC) combined with a coal or biomass gasification plant has the advantage of high conversion efficiency, and it produces sequestration ready N₂ free CO₂ exhaust. Although more fuel tolerant than other types of fuel cells, a SOFC must be capable of operating with a CO rich gasified fuel, which contains hydrocarbons and impurities, particularly hydrogen sulfide (H₂S). Hydrocarbons and H₂S are known to seriously and irreversibly degrade the performance of the standard nickel yttria stabilized zirconia (Ni-YSZ) SOFC anodes by coking and poisoning them through sulfur contamination.

To address these concerns, this project sought to develop replacement anode materials for Ni-YSZ that are not sensitive to coking and sulfur poisoning. The researchers identified two promising new oxide materials for study, LaSr₂CrFe₂O₉ (LSCrFe) and La_{0.8}Sr_{0.2}Cr_{0.82}Ru_{0.18}O₃ (LSCrRu) both mixed with Ce_{0.9}Gd_{0.1}O₂ (GDC). Tests of the anode materials LSCrFe and LSCrRu for coking and sulfur sensitivity found LSCrRu to be insensitive to coking in simulated coal gas containing CO but not hydrogen containing H₂S. The LSCrFe was insensitive to sulfur but not to coking. Importantly, both materials could be restored by heating in air. Although both of the anodes oxidized pure CO fuel in tests, they did so at a higher polarization resistance than for H₂ fuel. The performance loss was similar to that observed for Ni-YSZ, but the oxide anodes showed more stable performance in CO. These results contrasted to Ni-YSZ, which is seriously degraded by both coking and sulfur and cannot be restored. The researchers suggested several modifications of the materials for synthesizing a new anode that is insensitive to both coking and sulfur.

Keywords: SOFC, fuel cell, coal, biomass, gasification, sequestration, anode, coking, sulfur

2.2.2 Introduction

Biomass and coal are plentiful and domestically available energy sources for electricity generation.^{1,2,3} When they are burned in air they release greenhouse gases, primarily carbon

1 <http://biomass.ucdavis.edu/materials/reports%20and%20publications/2006/2006BiomassRoadmap.pdf>

2 http://ef.org/documents/4890_CAc coalShadow.pdf

dioxide (CO₂). While burned biomass is carbon neutral since it releases CO₂ recently captured in photosynthesis, burned coal is carbon positive, releasing new CO₂ into the atmosphere. In either case if the CO₂ effluent stream were pure, it could be easily captured, pressurized, and sequestered in geologic formations.⁴ However with combustion in air, the exhaust is strongly diluted with gaseous nitrogen (N₂) which must be removed, adding to the cost of sequestering the CO₂. Thus an environmentally benign and economical non-combustion process that yielded a more pure CO₂ effluent would be of great interest.

For this reason attention has been directed at coupling high temperature gasification of biomass and coal with a high temperature high efficiency solid oxide fuel cell (SOFC) for direct energy conversion into electricity. The gasification process produces syngas, a high energy fuel that consists of CO, H₂, and CH₄ as fuel for the cell. The SOFC oxidizes this fuel by selectively passing the oxygen from air through an oxygen selective electrolyte to generate electricity.⁵ The fuel and air oxidant do not mix. This bypasses the air combustion step in electrical generation and produces a carbon dioxide effluent stream largely undiluted by nitrogen. In present day SOFCs, a widely used anode is Ni-YSZ (yttria stabilized zirconia) cermet.⁶ However, Ni-YSZ suffers from the twin problems of coking of the anode (the fuel side) from the CO and CH₄ fuel and irreversible poisoning by sulfur impurities in the gas stream.⁷ Thus there is great interest in a new anode material that does not suffer from either coking or irreversible sulfur poisoning.

The benefit to California of such a new SOFC anode would be a large reduction in greenhouse gas emissions from generation of electricity. California's total system power is the sum of in-state generation and out-of-state imports. In 2008 total generation by coal accounted for 18.2 percent of the total system power (GWh), while biomass fueled generation accounted for 2.1 percent of the total.⁸ Coal and biomass fueled generation comprised 20.3 percent of California's electricity. The total system power for 2008 was 306,577 GWh. Thus coal and biomass combined accounted for 62,235 GWh of California's electricity consumption.⁹ Assuming that all coal and biomass generation would meet California's allowed GHG standard of 1100 lbs¹⁰ of CO₂ per MWh of electricity generated, this would release 6.85x10¹⁰ lbs or 31 MMT (million metric tons) of CO₂ into the atmosphere. A successful coal or biomass gasification

3 <http://www.xcelenergy.com/SiteCollectionDocuments/docs/corpcomm/ph-task46-sept02.pdf>

4 http://www.netl.doe.gov/technologies/carbon_seq/index.html

5 http://www.fuelcellmarkets.com/fuel_cell_markets/solid_oxide_fuel_cells_sofc/4,1,1,2503.html

6 doi:10.1016/S0167-2738(02)00359-4

7 <http://www.sciencemag.org/cgi/reprint/326/5949/52.pdf>

8 http://www.energyalmanac.ca.gov/electricity/total_system_power.html

9 <http://www.energy.ca.gov/2009publications/CEC-200-2009-010/CEC-200-2009-010.PDF>

10 [http://www.netl.doe.gov/publications/proceedings/09/CO2/pdfs/NETL%20OSAP%20CA%20GHG%20analysis%20\(Grol\)%20mar09.pdf](http://www.netl.doe.gov/publications/proceedings/09/CO2/pdfs/NETL%20OSAP%20CA%20GHG%20analysis%20(Grol)%20mar09.pdf)

and SOFC system would allow 31 MMT of CO₂ release per year to be captured and sequestered from the atmosphere.

The advancement of science proposed in this project is a coking and sulfur tolerant anode for SOFCs to enable a gasification SOFC system. The researchers proposed two novel anode materials for investigation. Both materials were conducting oxides and had been tested with H₂ fuel but not carbon bearing syngas necessary for gasification operation. One anode material employed a new oxide composition with mixed conductivity, and the other utilized a process that produced precipitated Ru metal nano-clusters on internal oxide surfaces. The researchers had recently demonstrated a mixed conducting composition of LaSr₂CrFe₂O₉ composition with the low resistance at 800° C that is necessary for 1 W/cm² output. The other material was La_{0.8}Sr_{0.2}Cr_{0.82}Ru_{0.18}O₃ with Ru substitutions on the Cr site. During the initial SOFC operation of this material, the Ru precipitates out as metal nano-clusters on internal surfaces of the porous anode, as shown in Figure 2. Ru metal is known to be a good catalyst, greatly increasing performance in hydrogen. It was thus proposed for operation in syngas. In this study, these new anode materials were compared to Ni-YSZ anodes in syngas where Ni-YSZ is known to fail. Both materials had promise for being coking and sulfur tolerant.

Figure 2: High Resolution Electron Microscope Image Showing Ru Metal Nano-clusters Formed on the Surface of (La,Sr)(Cr,Ru)O₃ Anode Surface after Exposure to Hydrogen Fuel at 7500 C for 45 Hours



2.2.3 Objectives

The goal of this project was to determine the feasibility of using new solid oxide fuel cell anodes for working with coal or biomass derived syngas without coking or degradation. The researchers established the following project objectives:

1. Synthesize two novel anode materials. Use high purity materials for initial studies.
2. Fabricate solid oxide fuel cells. Utilize self-supporting LSGM electrolytes and LSCoFe cathodes that combined contribute $<0.5 \text{ } \Omega\text{cm}^2$ to cell resistance at 800°C .
3. Modify fuel cell test setup for CO and H₂S containing fuels. Use CO flow rates up to 50 Standard Cubic Centimeters per Minute (SCCM) and H₂S concentrations up to 500 ppm. Introduce suitable safety precautions and procedures for using these gases.
4. Test SOFC anodes for effect of CO and CH₄ in syngas. Use CO/CH₄ reaction kinetics similar to H₂ or ability to shift CO to H₂ or reform CH₄. Demonstrate coking resistance in reasonable CO/CO₂ ratios and CH₄ contents.
5. Test SOFC anodes for effect of H₂S impurities in syngas. Demonstrate <10 percent cell performance degradation at realistic H₂S contents (up to 500 ppm). Demonstrate the device can operate for 500 hrs with <5 percent additional degradation.
6. Test SOFC anodes for anode regeneration. Show any performance degradation can be recovered by anode oxidation.
7. Conduct overall assessment. Based on acquired data, assess whether the new anodes provide useful improvements on Ni-YSZ.

8. Conduct preliminary analysis of implications for gasification power plants. Compare cost of new anodes with standard Ni-YSZ anodes. Estimate cost savings achieved by simplifying gasification plant.

2.2.4 Outcomes

1. The researchers synthesized two novel anode materials by solid state reaction using appropriate metal oxide powders. The new anode materials were $\text{LaSr}_2\text{CrFe}_2\text{O}_9$ (LSCrFe) and $\text{La}_{0.8}\text{Sr}_{0.2}\text{Cr}_{0.82}\text{Ru}_{0.18}\text{O}_{3-}$ (LSCrRu). Both anode materials were mixed with commercial $\text{Ce}_{0.9}\text{Gd}_{0.1}\text{O}_2$ (GDC) powder.
2. The researchers fabricated solid oxide fuel cells using the two new LSCrFe and LSCrRu anode materials. The fabricated cells used self-supporting $\text{La}_{0.9}\text{Sr}_{0.1}\text{Ga}_{0.8}\text{Mg}_{0.2}\text{O}_{3-}$ (LSGM) electrolytes and LSCoFe-GDC cathodes which combined contributed $\leq 0.5 \Omega\text{cm}^2$ to cell ohmic resistance at 800°C .
3. The researchers modified the fuel cell test setup for the safe use of CO and H_2S -containing fuels. They used multi-component gases in testing. The highest H_2S concentration tested was 500 ppm in H_2 .
4. The researchers tested the SOFC anodes for effect of CO and CH_4 in syngas. They used a surrogate coal gas fuel mixture of 41 percent CO, 16 percent CO_2 , 3 percent N_2 , and the balance of H_2 . The LSCrRu anode demonstrated freedom from coking under conditions where a Ni-YSZ baseline anode degraded with heavy coking and then failed by cracking. The LSCrFe anode showed performance degradation and the presence of carbon in EDS. This surprised the researchers. Total cell resistance was dominated by the ohmic resistance of the electrolyte plus cathode. The smaller polarization resistance was due to the anode. Anode polarization resistance was greatest for pure CO fuel.
5. The researchers tested the SOFC anodes for effect of H_2S impurities in pure H_2 . The LSCrRu anodes appeared susceptible to degradation when dilute 10 ppm H_2S was introduced to the H_2 gas stream. When the H_2S was removed there was only incomplete recovery. The LSCrFe anode demonstrated a slight reversible degradation at concentrations of 22 and 44 ppm H_2S in H_2 .
6. The researchers tested the degraded anodes, LSCrRu in H_2S and LSCrFe in CO, for regeneration of performance by re-oxidation with hot air in the gas stream. They observed good regeneration of performance, indicating removal of S and C deposits.
7. In their overall assessment, the researchers reported the LSCrRu anode can operate without coking even in pure CO. The LSCrFe anode displayed slight coking in CO rich fuels. With H_2S impurities, the relative advantage shifts, however, with LSCrFe showing less performance degradation than the LSCrRu anode. In all cases the two new materials exhibited superior performance to the baseline Ni-YSZ industry standard. Furthermore, the two new materials could be regenerated with a hot air treatment, while Ni-YSZ cannot. The measured power density of the two new cells was somewhat low. The

researchers reported this was not due to the new anodes but to the high ohmic resistivity of the relatively thick electrolyte used for support.

8. The researchers analyzed material costs of a new SOFC design with the new anodes and compared it with existing Ni-YSZ anode SOFCs. The new design was based on fabricating the cell on an inert SrTiO_3 support. Preliminary analysis produced a cost of \$20/kW for the SrTiO_3 approach, compared to up to \$100/kW for a Ni-YSZ based cell. The researchers did not find detailed information on the cost of gasifier SOFC power plants to enable them to make realistic estimates of the cost impact of the new anodes.

2.2.5 Conclusions

1. The solid state reaction technique for the two new anodes was successful.
2. The fabricated solid oxide fuel test cells with the new anodes were of low resistance ($<0.5 \Omega\text{cm}^2$ at 800°C).
3. The modified cell test bench was adequate for the safe use of hazardous CO and H_2S -containing fuels in testing.
4. In coking tests, the LSCrRu anode demonstrated freedom from coking in surrogate coal gas under conditions where a Ni-YSZ baseline anode degraded with heavy coking. The LSCrFe anode showed some indications of coking through the presence of carbon in EDS. While not conclusive, the researchers speculated that the LSCrFe oxide material precipitated small amounts of elemental Fe under reducing conditions, leading to the presence of the observed C. They speculated that lowering the concentration of Fe or replacing it with a less reducible cation such as Mn might provide coking resistance.
5. In tests for sensitivity to H_2S poisoning, the LSCrRu anodes appeared to degrade in performance after dilute 10 ppm H_2S was introduced in the H_2 gas stream. Importantly, when the H_2S was removed there was only incomplete recovery. The LSCrFe anode, however, demonstrated only a slight and reversible degradation at concentrations of 22 and 44 ppm H_2S in H_2 . Thus LSCrRu is inert under coking conditions and LSCrFe is largely inert under H_2S but not under coking conditions. Neither material is stable under both conditions.
6. After being degraded, LSCrRu in H_2S and LSCrFe in CO, the researchers tested both anodes for regeneration of performance by introducing air in the feed gas stream. They concluded good regeneration was achieved, indicating removal of S and C deposits.
7. The researchers concluded the LSCrRu anode can operate without coking even in pure CO, while the LSCrFe anode undergoes slight coking in CO rich fuels. With respect to H_2S poisoning, the relative advantage shifts to LSCrFe which shows less degradation than LSCrRu. In all cases both materials exhibited superior performance to baseline Ni-YSZ, the industry standard. Furthermore, once degraded, the two new materials could be regenerated with a hot air treatment while Ni-YSZ cannot.

8. The researchers concluded the material costs of a new SOFC design with the new anodes could be less expensive than Ni-YSZ anode SOFCs. However it is not yet possible to make realistic estimates of the cost impact of the new anodes on gasifier SOFC power plants.

The researchers did not fully meet the overall objective of demonstrating the feasibility of new solid oxide fuel cell anodes for working with coal or biomass derived syngas without coking or degradation. However they made good progress. The possibility of fine-tuning anode material composition or employing an anode of the two materials combined is worthy of investigation.

2.2.6 Recommendations

It is clear that a mixed anode material containing both Ru and Fe should be investigated for being inert to both coking and sulfur impurity conditions. Partial substitution or replacement of the Fe cation in LSCrFe is a promising avenue for reducing coking sensitivity. The researchers should continue to pursue their research in this area. The Program Administrator recommends the researchers develop commercial contact with a fuel cell manufacturer. The manufacturer can provide guidance on commercial issues and standards.

2.2.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California electricity supply, transmission, and distribution system. The main attraction would be the ability to produce electricity from coal and biomass derived fuels with a carbon dioxide exhaust stream undiluted by nitrogen, in contrast to direct combustion of these fuels with air. Since the exhaust stream would be undiluted by nitrogen, the carbon dioxide could be directly sequestered without passing through an expensive nitrogen separation step.

The benefit to California would be a large reduction in greenhouse gas emissions from generation of electricity. California's total system power is the sum of in-state generation and out-of-state imports. In 2008 total generation by coal accounted for 18.2 percent of the total system power (GWh), while biomass fueled generation accounted for 2.1 percent of the total.¹¹ Coal and biomass fueled generation comprised 20.3 percent of California's electricity. The total system power for 2008 was 306,577 GWh. Thus coal and biomass combined accounted for

¹¹ http://www.energyalmanac.ca.gov/electricity/total_system_power.html

62,235 GWh of California's electricity consumption.¹² Assuming all coal and biomass generation meets California's allowed GHG standard of 1100 lbs¹³ of CO₂ per MWh of electricity generated, this combined generation would release 6.85x10¹⁰ lbs or 31 MMT (million metric tons) of CO₂ into the atmosphere. A successful coal or biomass gasification and SOFC system would allow this amount of CO₂ release per year to be captured and sequestered.

2.2.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.2.8.1 Marketing/Connection to the Market

The Program Administrator is not aware of any pertinent new marketing information.

2.2.8.2 Engineering/Technical

The researchers reported they secured NSF funding. This additional funding will allow them to continue engineering development.

2.2.8.3 Legal/Contractual

The researchers reported a search of the literature indicated patentability. They found one existing patent the Patent Office might take to be prior work.

2.2.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

It is premature at this stage to address these concerns. However the researchers are aware of these issues.

2.2.8.5 Production Readiness/Commercialization

Important development and testing questions remain to be answered before production readiness can be established. The researchers reported an industrial or commercial company has expressed interest in helping them take their technology to market.

12 <http://www.energy.ca.gov/2009publications/CEC-200-2009-010/CEC-200-2009-010.PDF>

13 [http://www.netl.doe.gov/publications/proceedings/09/CO2/pdfs/NETL%20OSAP%20CA%20GHG%20analysis%20\(Grol\)%20mar09.pdf](http://www.netl.doe.gov/publications/proceedings/09/CO2/pdfs/NETL%20OSAP%20CA%20GHG%20analysis%20(Grol)%20mar09.pdf)

2.3 Thermochemical Processes Platforms to Utilize Crude Glycerin for Hydrogen Production and Electricity Generation

Awardee: University of Arkansas Division of Agriculture

Principal Investigator: Samy Sadaka

2.3.1 Abstract

This research project investigated a new avenue of utilizing glycerin in electricity generation using a gasification process integrated with a Stirling engine generator. Glycerin ($C_3H_8O_3$) is a byproduct of biodiesel production from vegetable oil or animal fat. With California expanding its use of biodiesel, crude glycerin production could reach 40 million gallons per year. Glycerin gasification produces gas with medium heating value that can be used in various thermal cycle engines. In this project researchers gasified glycerin in an externally heated fixed bed gasifier. They analyzed the effects of bed temperature (650° C, 700° C, and 750° C), water to glycerin ratio (0:100, 15:85, and 30:70) and a catalyst on the product's yield (gas, liquid, and char). They also analyzed gas composition and heating value. The gas production rate reached 66 percent of the product weight during gasification of crude glycerin with the addition of a catalyst. The reaction produced synthesis gas with 13640 MM Btu/m³. A 55 kW Stirling engine generator could be fueled by gasifying 48 kg/h glycerin, based on heat content and engine efficiency. Biodiesel production plants could benefit from the proposed technique by generating electricity on site.

Keywords: Glycerin, gasification, hydrogen, Stirling engine, electricity

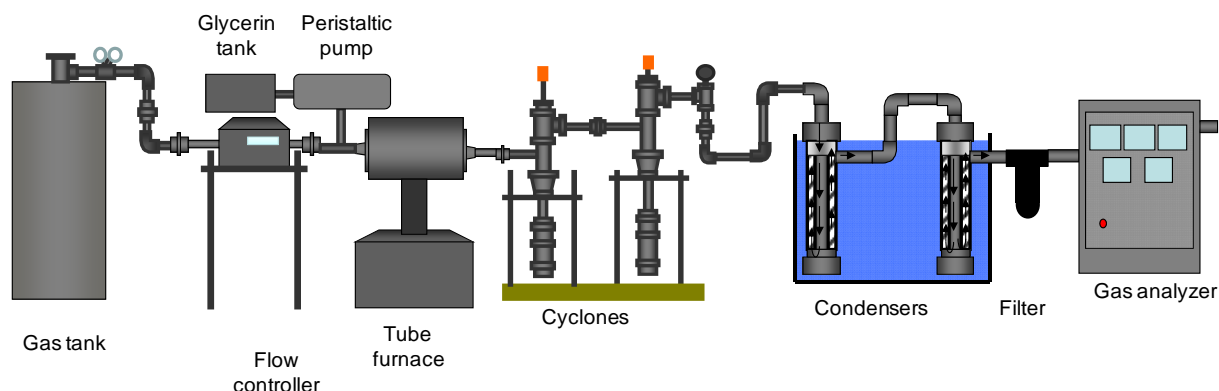
2.3.2 Introduction

Biodiesel production in California is currently about 200 million gallons per year and is expected to grow based on various policies such as the Low Carbon Fuel Standard. Biodiesel production produces biodiesel and crude glycerin as a byproduct of the transesterification process. Glycerin is produced in a ratio of approximately 1:10 weight glycerin to biodiesel. The amount of glycerin production increased from 0.2 million gallons in 2000 to 25 million gallons in 2006. Glycerin production in California could reach 40 million gallons annually. Crude glycerin contains excess alkali metal catalyst, salts, excess methanol, and unrecovered biodiesel which degrade its market and industrial value. Finding alternative uses for crude glycerin, such as gasification for energy production, to higher value product has become essential.

Using crude glycerin directly is not technically feasible in most thermal engine cycles because of the high levels of salts and alkali metals and inherent viscosity of glycerin. Some form of cleanup is necessary to use this resource for energy. Glycerin gasification steam reforming is a potentially attractive technique to convert the crude glycerin to a useable fuel. This may be especially attractive for on-site use at biodiesel production facilities to self generate a portion of their electrical demand and ease handling for transport of the crude glycerin.

In this project researchers tested the feasibility of crude glycerin clean-up by gasification for integration with a Stirling engine for electric power generation. Figure 3 illustrates the test apparatus. In commercial application the gas analyzer would be replaced with a thermal engine generator such as a Stirling engine.

Figure 3: A Schematic Diagram of a Fixed Bed Gasifier



2.3.3 Objectives

The goal of this project was to determine the feasibility of gasifying crude glycerin and combusting the resulting synthesis gas in an integrated Stirling engine. The researchers established the following objectives:

1. Conduct several experiments to confirm that crude and pure glycerin can be gasified to produce fuel gas with low tar (less than 10 mg/mN³) and low particulate concentrations (less than 160 mg/m³ particulate).
2. Design and construct a catalytic reactor system (guard bed, steam reformer, high and low temperature reactor). Test the performance of the catalytic reactor system. Produce synthesis gas with medium BTU about 125–165 BTU/ft³.
3. Test steam reforming of synthesis gas. Evaluate the factors that maximize hydrogen production. Achieve hydrogen concentration of the producer gas as high as 27 percent.
4. Characterize the flue gas produced via the combustion process of producer gas or syngas. Modify the burner as needed. Produce concentrations of the H₂, CO, and CH₄ in the flue gas as low as 1 percent.
5. Evaluate the energy content of the flue gas as well as the concentrations of the particulate and contaminate. These are the required parameters identified by Stirling engine manufacturing companies.

2.3.4 Outcomes

1. The researchers observed that the producer gas yield increased by 26.2 percent in the case of pure glycerin with catalyst when the bed temperature increased to 750° C from 650° C. The researchers also observed that the bed temperature had a negative effect on the liquid yield. Increasing the bed temperature to 750° C from 650° C decreased the liquid yield by 17.0 percent in the case of crude glycerin with no catalyst. Pure glycerin with no catalyst showed 14.7 percent reduction of the tar yield when the bed temperature increased to 750° C from 650° C.
2. The researchers measured the effect of increasing the water to glycerin ratio. This increased the gas yield. They observed the highest increase in the gas yield (31.5 percent) in the case of pure glycerin with catalyst. However the researchers measured the lowest increase in the gas yield (8.7 percent) in the case of pure glycerin with no catalyst. They measured a 29.5 percent reduction of the produced liquids in the case of pure glycerin with catalyst. Char yield also decreased with the increase in the water to glycerin ratio.
3. The researchers obtained a maximum hydrogen mole fraction of 49.7 percent in the case of crude glycerin with catalyst at bed temperature of 750° C. However they observed the lowest hydrogen mole fraction of 34.8 percent in the case of crude glycerin with no catalyst at bed temperature of 650° C. The researchers found that methane mole fractions increased with increase in the bed temperature.
4. The researchers found that increasing the water to glycerin ratio from 0:100 to 30:70 increased the hydrogen production by 23.7 percent for crude glycerin with catalyst. However, increasing the water to glycerin ratio from 0:100 to 30:70 increased the hydrogen production by only 2.2 percent for pure glycerin with no catalyst.
5. The researchers found that the highest heating value of the synthesis gas (13640 MM Btu/m³) was obtained in the case of crude glycerin with catalyst at a temperature of 750° C. However, the lowest heating value of the producer gas (9.4 M J/m³) resulted from the case of pure glycerin with catalyst at 650° C.
6. The researchers created a scenario of fueling a Stirling engine generator system using the energy content in the producer gas.

2.3.5 Conclusions

The researchers demonstrated that gasification of crude glycerin is feasible, but much work remains. About 66 percent of the glycerin weight was converted to a medium heating value gas. Gasification and steam reforming of glycerin created producer gas with hydrogen content up to 49.7 percent. Producer gas with up to 13640 MM Btu/m³ was produced. This gas can be combusted efficiently to power a Stirling engine generator. As an example, a 55 kW Stirling engine generator could be fueled by gasifying 48 kg/h glycerin.

2.3.6 Recommendations

The researchers should focus on optimizing the glycerin gasification process. They should undertake an extended time test of the catalyst and measure conversion efficiency over weeks

or months to determine if catalyst poisoning or degradation occurs, including as a function of alkali levels in the crude glycerin. The researchers should determine the envelope of performance and operating characteristics that affect synthesis gas output and quality and reduce performance uncertainty.

The researchers should seek joint cooperative agreements with engine manufacturers to determine feasibility of using the produced gas. Feasibility should consist of demonstrating adequate yield and fuel quality from gasified crude glycerin to run an engine over extended time, as well as dealing with appropriate disposal of the byproducts such as char. The researchers should evaluate the electrical requirements at biodiesel production facilities to determine appropriate sizing of gasification and power block components. They should determine if multiple train configurations are appropriate for biodiesel facilities, recognizing their differing operational characteristics.

The researchers should consider other engines in addition to Stirling engines. Stirling engines are not widely available, and few technicians know how to maintain them. New products that rely on both a new fuel and a new engine are not likely to achieve rapid commercial success. The researchers should consider reciprocating engines or microturbines to minimize the engine based risk while introducing a new fuel.

After completion of engineering and technical issues, the researchers should investigate patentability and apply for patents as appropriate. They should then, if warranted, begin to publish their results in trade journals.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.3.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California electricity supply system.

Biodiesel producers in California would be early beneficiaries of this technology since they would be able to have a steady market for their produced glycerin which otherwise would be considered waste. This would have the added benefit of improving the cost effectiveness of biodiesel production and enhancing its growth. Based on the findings from this research, if 40 million gallons of crude glycerin were gasified each year, it could power over 600 55 kW Stirling engine generators, with each consuming about 66,000 gallons per year. Assuming a 75 percent capacity factor for the generators, the electricity production would be approximately 204 million kWh per year, the equivalent of over \$20 million in retail electricity.

2.3.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.3.8.1 Marketing/Connection to the Market

The researchers have not worked directly with any major manufacturers or system packagers to develop necessary market or technical metrics for this technology. They have surveyed potential customers, including biodiesel production facilities.

2.3.8.2 Engineering/Technical

The researchers planned to integrate a Stirling engine with the existing fluidized bed gasifier. They were seeking funds to purchase a Stirling engine and continue the development.

2.3.8.3 Legal/Contractual

At the end of the project the researchers did not have patent protection, nor is it clear that the concept can be patented.

2.3.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

There are no identified environmental or safety risks at this time. Until further development and feasibility is completed, quality plans are premature.

2.3.8.5 Production Readiness/Commercialization

The concept is not ready for production or commercialization. There is considerable work, as outlined above, necessary before production or commercialization can be considered.

2.4 Novel Cogeneration Process for Wastewater Treatment Plant Operations

Awardee: C/e- Solutions, Inc.

Principal Investigator: James C. Smoot

2.4.1 Abstract

The primary goal of this project was to determine the feasibility of converting natural components of wastewater treatment plant biosolids into fuel and then to determine the feasibility of reducing biosolids disposal costs via enhanced water reclamation techniques.

Key performance objectives for this project were to demonstrate:

- Biomass growth conditions resulting in at least 20 percent biomass as carbon storage compound.
- A system that removes 98 percent of the water from biomass.
- A process that produces an 80 percent yield of fuel from carbon storage compound.

The project's sole cost objective was the development of a system that is cost competitive with other renewable energy technologies.

The project resulted in data showing that biofuel precursor production, under a variety of conditions including those found at wastewater treatment plants (WWTPs), routinely achieved the performance objectives. The research met the dewatering technical objective under a variety of conditions when acetone was used in conjunction with heat. However, techno-economic analysis indicated that costs were not competitive with standard air drying technologies (\$0.19 per kg of biosolids).

Bench scale biofuel production resulted in quantitative recovery of biofuel compounds under low reactant to precursor ratios. The researchers projected the processes developed could produce a mixed liquid biofuel for \$0.08 per kWh (production cost was \$0.59 per kg; energy density equals approximately 27 MJ per kg; 0.28 kWh per MJ). This is competitive with other renewable energy technologies (e.g., biogas \$0.09—\$0.16 per kWh, wind approximately \$0.08 per kWh, and solar PV approximately \$0.30 per kWh).

Process scale-up is required to validate the techno-economic modeling results and to demonstrate that the process is a suitable approach for commercial application of the technology.

Keywords: Biofuel, biosolids, waste-to-fuel, waste-to-energy, techno-economic modeling

2.4.2 Introduction

Energy derived from biomass is an important component of California's energy future as evidenced by the Governor's establishment of the Bioenergy Interagency working group. This

group is charged with focusing the forces of state government on the task of making major steps toward the widespread use of biomass to produce clean, renewable transportation fuels or electricity.¹⁴

In April 2006 the Governor reinforced the importance of biomass energy in Executive Order S-06-06.¹⁵ Two important goals of the Executive Order state:

- By 2010, 20 percent of the state's biofuels should be produced within California, increasing to 40 percent by 2020 and 75 percent by 2050.
- By 2010, 20 percent of the state's renewable electricity should be generated from biomass resources within California, maintaining this level through 2020.

However, according to the Energy Commission's 2009 Biennial Report, new biomass facilities face barriers to development.¹⁶

This research evaluated the potential of using natural components of wastewater treatment plant (WWTP) sludge (commonly referred to as biosolids) as clean burning fuels. Another important task was to examine methods to reduce the cost of disposal of biosolids at these facilities through enhanced water reclamation techniques.

Critical feasibility issues addressed by this research project included a determination of how to:

- Optimize biosolids for fuel production
- Dewater biosolids in an energy/cost effective manner
- Transform biosolids into a clean burning fuel in an energy efficient and cost effective manner

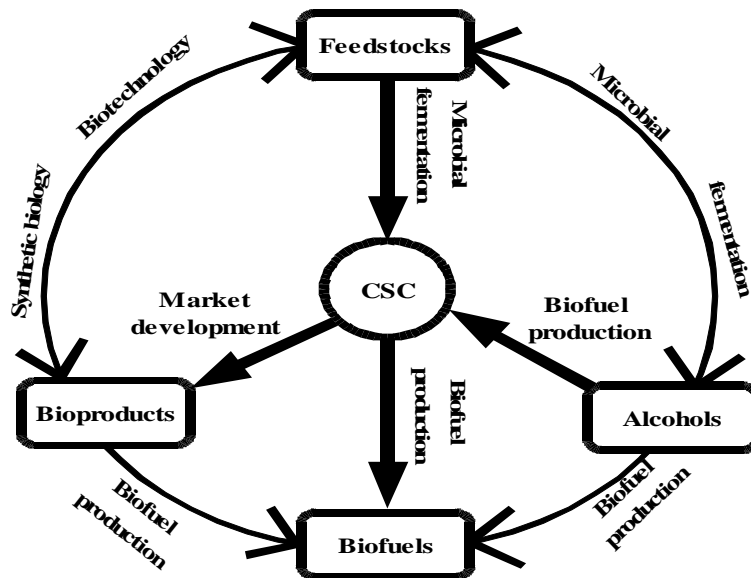
The grantee's proposed cogeneration process, depicted below, transforms treatment of WWTP biosolids into a bio-refinery process. The project focused on developing processes that convert naturally occurring carbon storage compounds into a liquid biofuel. If successful, this process could be applied to the 16,000 WWTPs in the United States, 800 of which are located in California.

14 <http://www.energy.ca.gov/biomass/index.html>

15 Executive Order S-06-06 (PDF file)

16 California Energy Commission, 2009 *Integrated Energy Policy Report*, Final Commission Report (December 2009), CEC -100-2009-003-CMF, p 6.

Figure 4: Schematic of Overall Process



2.4.3 Objectives

Under this grant the researchers hoped to determine the feasibility of using natural components of wastewater treatment plant (WWTP) sludge, commonly known as biosolids, as clean burning fuels and to determine the feasibility of reducing biosolids disposal costs via enhanced water reclamation techniques. The researchers proposed the following performance and cost objectives to measure the success of this research:

1. Demonstrate growth conditions that result in at least 20 percent biomass as carbon storage compounds (CSC). According to the researchers, this CSC production rate was chosen to allow for reasonable production throughput.
2. Demonstrate a system that removes 98 percent +/- 2 percent of the water from biomass to achieve efficient biofuel production.
3. Demonstrate a process that produces an 80 percent yield of fuel from carbon storage compound. This fuel production rate was chosen to allow for reasonable production throughput.
4. Demonstrate with process Gantt charts the required performance benchmarks needed for commercially viable implementation of the process.
5. Demonstrate via engineering drawings and specifications a pre-commercial reactor prototype suitable for testing wastewater treatment plant biosolids.
6. Achieve CSC and biofuel production costs of less than \$26.24 per ton of biosolids.
7. Achieve biosolids drying costs less than \$31.20 per ton of biosolids.

2.4.4 Outcomes

1. The research identified carbon storage compound (CSC) yields ranging from 17.5 percent to 100 percent of the total carbon substrate when systems were fed large amounts of CSC precursor compounds producing the greatest CSC yields. The results demonstrated that the predicted 20 percent growth rate is likely.
2. The researchers accomplished the performance objective of 98 percent dewatering in conjunction with heating for 60 minutes in all experimental treatments. However when double washed with 35 percent acetone, the sample reached dryness after 45 minutes of heating.
3. Using an integrated acid esterification solvent purification process, the researchers reported consistently high yields of biofuels in the laboratory, well above the 80 percent yield originally anticipated.
4. The researchers projected, based on the process developed for this project, the cost to produce one kilogram (kg) of biofuel to be \$0.59 when credits for reduced biosolids tipping fees and offsets for utility costs were included in the analysis. They concluded the production cost was economically viable when considering the market price of intermittently available renewable energy sources (biogas \$0.09 to \$0.16 per kWh, wind approximately \$0.08 per kWh, and solar PV about \$0.30 per kWh) and other liquid biofuels such as ethanol at approximately \$0.75 per kg.

In addition, the researchers found that valuable chemicals were produced as co-products of the process. Additional compound separation and purification development efforts would be necessary to demonstrate suitable commercial grade chemicals. However the researchers observed that the compounds' market values ranged from \$10 per kg to \$30 per kg, after a 90 percent reduction in current market value was set aside for purification costs. Further market analysis is required to determine feasibility in offsetting fuel costs. Additional income from biodiesel is possible, although it was a relatively minor constituent of the biofuel/bioproducts crude extract.

5. Appendix I of the project's Final Report contains schematics demonstrating material flows from CSC precursor synthesis through biofuel production, as well as drawings of a prototype solvent recovery system and esterification reactor. It should be noted that Appendix I is confidential.
6. The researchers estimated the cost of producing CSC to be \$20 per ton of biosolids, well under the stated objective of \$26.24 per ton. On an annual basis and taking into account the costs associated with the production of CSC, the techno-economic projected costs related to production and extraction of biofuel was \$0.59 per liter.
7. The researchers found that sludge dewatering using acetone was approximately on par with the cost of conventional air drying (\$0.15 vs. \$0.19 per kg of biosolids, respectively). However biosolids, after dewatering with acetone, still contained 21.3 percent water and required air drying to complete the drying process. As a consequence, the researchers

found complete drying of the biosolids led to a significant cost increase and would be less cost effective than drying with an air system that uses the process heat recovered from the esterification and extraction processes. Further, it would exceed the objective of maintaining a cost for drying below \$31.20 per ton of biosolids.

2.4.5 Conclusions

The researchers met or exceeded most of the performance objectives set out for this project. They demonstrated a lower than anticipated cost of production of CSC, resulting in an estimated cost of biofuel production and extraction of \$0.59 per liter. While Objective 7 was not met using acetone, an air drying system that uses the process heat recovered from the esterification and extraction processes would meet the cost objective.

2.4.6 Recommendations

The Program Administrator supports the six recommendations for further research as proposed by the researchers. Further research should:

- Scale up the WWTP biosolids-to-biofuel process to test and validate the results of this grant.
- Expand the feedstock capacity to include agricultural wastes as an additional feedstock.
- Identify more cost effective esterification reactor materials to further lower process costs.
- Determine methods to overcome the higher cost of solvent dewatering.
- Research the potential role of WWTP bio-refinery pathways in a larger distributed energy mix.
- Determine the potential for the production of ethanol at WWTP bio-refineries.

When scaling the proposed technology to commercial size, the biosolids and resulting fuels should be closely monitored to assure their continued environmental safety.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.4.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system

- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research would come from increased reliability of California's electricity system.

If the project were successfully completed and widely adopted, WWTPs could significantly add to the availability of biofuel production in the state while reducing the amount of biosolids at these facilities. According to the grantee, there are over 800 WWTPs distributed throughout California.

The creation of a distributed network of California biofuels producers also has the potential for creating a network of renewable electricity generators at the WWTP. This electricity generation fueled by renewable biofuels could add a significant new source of renewable electricity to the California system and thereby increase the system's reliability. Since these water treatment facilities are located near population centers, the addition of on-site renewable electricity generation could provide greater voltage support to the electricity system and further enhance reliability.

The potential amount of electricity that might be added to California's electricity system would ultimately depend on how widely the proposed technology is adopted. In their Final Report, the researchers estimated biofuel recovery from WWTP biosolids could harvest 976,000 tons per year of biofuel in California, approximately 217 kWh per Californian per year. With a population estimated at 37 million in 2009, this would represent a significant addition to California's renewable portfolio.

2.4.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.4.8.1 Marketing/Connection to the Market

The research performed is strongly connected to the needs of the market. According to a July 2009 report from Yale University, similar work is being performed around the world by a wide variety of research teams, including NASA.¹⁷

The researchers worked closely with the California Water Resource Control Board to determine the number of WWTPs in California. This cooperation could continue.

17 Greg Breining, "From the Sewage Plant, the Promise of Biofuel." *Yale Environment* 360 (July 2009).

2.4.8.2 Engineering/Technical

None identified during review.

2.4.8.3 Legal/Contractual

No additional information received.

2.4.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

The researchers have not developed these plans.

2.4.8.5 Production Readiness/Commercialization

Scale-up of the proposed technology is required before commercialization.

2.5 Air Independent Internal Oxidation Steam Generator

Awardee: Clean Engen Group LLC

Principal Investigator: George Touchton

2.5.1 Abstract

This research determined the feasibility of an air independent internal oxidation (AIIO) process using metal oxides/peroxides to convert fuel to electricity and/or heat. The researchers evaluated existing research, created flow sheet models, and built a laboratory scale test reactor to generate data for a wide range of candidate metal oxides/peroxides and fuels. They then created preliminary designs at pilot and prototype scales.

Researchers carried out extensive testing and analysis on a laboratory scale test reactor in the High Temperature Gas Dynamics Laboratory at Stanford University. Results indicated such an AIIO system is feasible. Of the six candidates, copper oxide ranked highest due to its low fuel/oxide ratio, lack of undesirable species, non-toxicity, and easy handling/availability.

Analysis and experimental data indicated that zero gaseous pollutant and greenhouse gas emissions are feasible. Calculations suggest AIIO has the potential to capture over 90 percent of fuel energy to produce work and/or process heat, well above that of existing boilers.

Keywords: Air independent internal oxidation, AIIO, oxygen carrier, carbon capture, CO₂ capture, chemical looping, copper oxidation, biomass, coal

2.5.2 Introduction

Electricity generation and organic waste disposal create significant air quality issues since they release large quantities of greenhouse gases. Present biomass driven generation provides a partial solution, but costs are high and sequestration of resultant greenhouse gases is typically incomplete.

A process that would yield heat energy for generation at lower costs with little or no greenhouse gas emissions would provide both economic and environmental benefits to California ratepayers, as well as to the state as a whole.

The researchers proposed to demonstrate feasibility of an air independent internal oxidation power plant with zero pollutant and greenhouse gas emissions using a variety of fuels, including selected biomass materials, at better heat rates than existing boilers.

2.5.3 Objectives

The goal of this project was to determine the feasibility of an air independent internal oxidation (AIIO) system using metal oxides/peroxides¹⁸ to convert fuel¹⁹ to electricity and/or heat. The researchers established the following project objectives:

1. Identify and report adiabatic reaction temperature; heat available to power (electricity + heat); flow rate of oxidant; flow rates and properties of oxidation products; oxygen carrier available for regeneration; CO₂ emitted or available for capture; air pollutant formation; and material handling, safety, and cost issues.
2. Determine and report reaction completion; heat release/adiabatic temperature; side reaction products; material safety, stability, durability, and handling.
3. Develop and report a candidate fuel/oxygen carrier (OC) matrix and a rationale for choices.
4. Develop and report process requirements from flow sheet analysis: state points, temperatures, pressures, flow rates, enthalpies.
5. Design and build bench scale test facility.
6. Check out and start up test equipment.
7. Perform experimental screening and report results.
8. Confirm and report the feasibility of zero gaseous pollutants and GHG emissions.
9. Determine and report analytical functions and process models and experimental parameter determination and validation.
10. Develop a design for next stage product testing.
11. Develop and report a prototype design including process one line flow chart, process interconnect and instrumentation diagram, bill of materials, capital and O&M cost projections, and projected performance.

18 Initial candidates were Fe₂O₃-Fe₃O₄, BaO₂-BaO, NiO-Ni, Mn₂O₃-Mn₃O₄, CuO-Cu, SrO₂-SrO, CaO-CAO₂, CaS-CaSO₄, CoO-Co₃O₄, Co+Ni

19 Candidate fuels were Priority 1: natural gas, rice straw, corn stover, coal, and Priority 2: ethanol, used cooking oil, biodiesel, and wood waste.

2.5.4 Outcomes

1. The researchers determined open loop reactor equilibrium results for the candidate oxygen carriers and indicated that a single oxygen carrier system was adequate for all Priority 1 fuels. CO₂ emissions were less than 1 ppmv for all systems, and greater than 90 percent of CO₂ was available for capture. Researchers predicted CO, SO₂, and SO₃ to be essentially zero. They did not predict NO_x formation at the modeled bed operating temperatures.
2. The researchers analyzed a full two reactor closed loop system with a commercial software package for 24 possible pairings of candidate metal oxides and fuels. They selected this method over an open loop approach to obtain more accurate mass, species, and energy balances. This step generated the data necessary to meet Objectives 2–4 as planned.
3. Researchers used data from literature research, open loop equilibrium analysis (Objective 1), and closed loop equilibrium flow sheet analysis (Objective 2) to screen out four of the initial oxygen carrier candidates for cost, pollutant formation, or regeneration potential. They ranked the remaining six as follows: Fe₂O₃-Fe₃O₄, BaO₂-BaO, NiO-Ni, Mn₂O₃-Mn₃O₄, CuO-Cu, SrO₂-SrO.
4. Parameters from Objective 2 led to a final ranking of three oxygen carrier candidates as viable for further study: CuO-Cu, Fe₂O₃-Fe₃O₄, Mn₂O₃-Mn₃O₄.²⁰ All three had similar combined work and heat outputs across an 800 to 1000° C range of fuel oxidation reactor temperatures. The final ranking of copper over iron reflects its much lower metal oxide to fuel mass ratio.
5. The researchers designed and built a laboratory scale reactor in the High Temperature Gasdynamics Laboratory at Stanford University.
6. They completed check out and start up of the test equipment.
7. Testing using CuO-Cu and Fe₂O₃-Fe₃O₄ yielded data for temperature, flow rate, and gas composition. The researchers performed additional experimental work using thermogravimetric analysis, x-ray diffractometry, and scanning electron microscopy to verify and enhance test data. They did not test Mn₂O₃-Mn₃O₄ further due to material safety handling issues and discovery of a potential side reaction of carbide formation.²¹
8. Researchers demonstrated the copper and iron oxygen carriers to be capable of producing power and/or heat with zero gaseous pollutants and GHG emissions using corn stover, rice straw, coal, and methane. They found both carriers to be capable of reduction and regeneration without significant material loss.

20 Rejected candidates: BaO₂-BaO due to formation of high quantities of side reaction products at maximum operating temperatures, SrO₂-SrO due to very high pressures required for regeneration, and NiO-Ni due to carcinogenic properties.

21 The issue of potential carbide formation is an item for future study.

9. The researchers conducted an analysis of reactors, turbines, compressors, pumps, and heat exchangers operating with a copper oxygen carrier and rice straw as fuel. For a 5 MWe plant, analysis suggested a net plant efficiency of 25 percent (13,648 Btu/kWh heat rate), including energy required for CO₂ liquefaction. Present biomass plants are likely only to match this efficiency if they do not include energy for CO₂ capture.
10. The researchers designed a detailed pilot scale test unit, including two reaction chambers, two cyclone separators to allow the bed material to be switched between reactors as gas products are exhausted, and capability to add make-up bed material.
11. The researchers completed a preliminary prototype design study, including a one line flow chart, interconnect and instrumentation diagrams, and bill of materials for major equipment. They did not complete the planned cost projections and performance projections.

2.5.5 Conclusions

The research proved the feasibility of an air independent internal oxidation system using metal oxides/peroxides to convert fuel to electricity and/or heat. Top candidates were the copper and iron oxides, which were shown to yield zero gaseous pollutants and GHG emissions at projected heat rates better than current biomass plants.

Preliminary modeling and screening successfully identified three of the initial oxygen carrier candidates as viable for further testing. The researchers expected at least 90 percent of the CO₂ created to be available for capture in the process.

The researchers confirmed their hypothesis by showing at least two of the candidate oxygen carriers were capable of producing power and/or heat with zero gaseous pollutants and GHG emissions with several fuels. These results were obtained with CuO-Cu and Fe₂O₃-Fe₃O₄ after screening out Mn₂O₃-Mn₃O₄ (due to material handling safety issues), and using corn stover, rice straw, coal, and methane. The analysis of a 5 MWe plant using copper and rice straw suggested a heat rate superior to that of present biomass plants when such plants include energy for CO₂ sequestration.

The detailed pilot scale test unit design and preliminary prototype design study provided useful information for future research and economic analysis. Although the researchers did not estimate projected capital and O&M costs and plant performance, given the early stage of prototype development, this would have of necessity been a very general projection and is not a significant omission.

2.5.6 Recommendations

The Program Administrator recommends moving forward to a pilot-scale demonstration. As this is done, selection of the fuel(s) to be used should include weighting for their quantities in California and attendant waste disposal difficulties.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the

Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.5.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California electricity supply. These benefits accrue from the expected higher efficiency of an AIIO plant over conventional boilers and its ability to allow conversion of biomass fuels such as rice straw and wood waste to useful energy while sequestering virtually all of the CO₂ produced.

2.5.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.5.8.1 Marketing/Connection to the Market

Clean EnGen Group, LLC plans to sell and install its power generation systems at its customers' sites. There is no evidence they plan to engage any other marketing organization. The researchers indicated they intended to partner with established CHP installers.

2.5.8.2 Engineering/Technical

The researchers indicated they could move from this proof of feasibility project directly to a pilot scale test in a two to three year time frame. They saw no engineering barriers to this plan.

The researchers indicated the pilot scale plant was needed before a full demonstration product could be built.

2.5.8.3 Legal/Contractual

The researchers indicated a patent application has been filed. If the process operates as intended, no additional legal barriers appear likely to arise.

2.5.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

The researchers' recommendation for proceeding to a pilot-scale demonstration project is the logical next step and can address issues of reliability and safety.

2.5.8.5 Production Readiness/Commercialization

The researchers intend to commercialize the technology in partnership with an established combined heat and power installer. A period of two to three years to complete pilot testing and ready the process for commercialization is highly aggressive and dependent on timely additional research and development funding.

2.6 Energy Storage for Grid and Renewable Sources

Awardee: Enstorage Israel Ltd.

Principal Investigator: Arnon Blum

2.6.1 Abstract

The goal of this project was to develop an energy storage technology for electrical generation systems. Energy storage offers many benefits to both utilities and consumers, including the ability for utilities to size their systems for average rather than peak demand, thereby avoiding or delaying costly system upgrades. Other benefits include making intermittent renewable energy sources, such as solar and wind, more economically attractive. For consumers, energy storage provides the capability to lower time-of-use payments by storing energy at low cost, low demand times and releasing it for generation at high cost, high demand times.

The approach investigated in this project was the scale-up of a new type of regenerative fuel cell (RFC) or flow battery using a low cost electrolyte, hydrogen bromide (HBr), and a proton conducting membrane. The electrolyte chemicals used were 10 to 20 times lower on a dollars per kWh basis compared with competing energy storage systems. During charging the RFC functioned as an electrolysis unit where HBr in aqueous solution was converted to HBr_3 and gaseous H_2 , which was separated by a proprietary membrane. The separated hydrogen gas was stored in external cylinders, while HBr_3 was stored in the original electrolyte tanks. When the system was switched to discharge mode it functioned as a fuel cell in which H_2 was supplied from the cylinders and HBr_3 was converted back to HBr. The research starting point was taken from previous work on small 5cm^2 single test cells with output up to $1.5\text{W}/\text{cm}^2$. The measured electricity-to-electricity efficiency approached 80 percent in the small test cells, compared to 40

percent for hydrogen/air fuel cells. Here the research demonstrated scale-up to 100cm² area cells and five cell stacks of output 100W with storage capacity of one to three hours. The researchers measured round trip electric-to-electric efficiency at 63 percent.

Keywords: Energy storage, regenerative fuel cell, hydrogen bromine, proton conducting membrane, load leveling

2.6.2 Introduction

The goal of this project was to develop an energy storage technology for electrical generation systems. Transmission and distribution systems deliver electricity where it is needed. Energy storage can deliver it when it is needed.²² In other words, energy storage mediates between variable sources and variable loads.²³ There are many benefits to this capability, including allowing utilities to size their systems to average demand rather than to peak demand, to include new but intermittent energy sources, and to enhance dispatchability to the grid operator. By sizing for average rather than peak load a utility can avoid or delay expensive capacity upgrades. Important renewable energy sources such as solar and wind suffer from the problem of intermittency due to variable diurnal input in the case of solar and unpredictable variations in wind speed in the case of wind power. In addition, they lack the capacity for dispatchability which would allow a utility operator to bring them online in times of insufficient grid output. What is needed for renewable sources is a means of storing energy during times of high output with the capability of rapidly releasing or discharging energy from storage during times of excessive demand. Energy storage methods generally fall into one of four categories: electrochemical (e.g. ultra capacitors, batteries, flow batteries, fuel cells), mechanical (pumped hydro, compressed air, flywheels), electrical (superconducting magnets), and thermal (e.g., molten salt power tower receivers).^{24,25} If one of these methods could be developed with the right combination of storage capacity, discharge speed, reliability, and low cost, the payoffs could be substantial.

A recent study analyzed the payoff to California of 13 applications and/or financial benefits associated with the use of energy storage.⁵ This study determined financial viability by the benefit to cost ratio over a 10 year storage plant life. It grouped the applications into three categories: grid system, end user/utility customer, and renewables (primarily wind and solar). In general it found benefits fell into the categories of avoided cost or increased revenue, reduced time-of-use energy costs, and reduced demand charges. While difficult to assess with precision due to uncertainties of future requirements, the cost savings were substantial. Overall the 13 applications for storage yielded an estimated 10 year economic potential benefit of over \$13B to

22 http://mydocs.epri.com/docs/CorporateDocuments/EPRI_Journal/2010-Summer/1021445_EnergyStorage.pdf

23 <http://www.netl.doe.gov/technologies/coalpower/fuelcells/seca/tutorial/TutorialIII files/TutorialIII.pdf>

24 http://www.nrel.gov/learning/eds_energy_storage.html

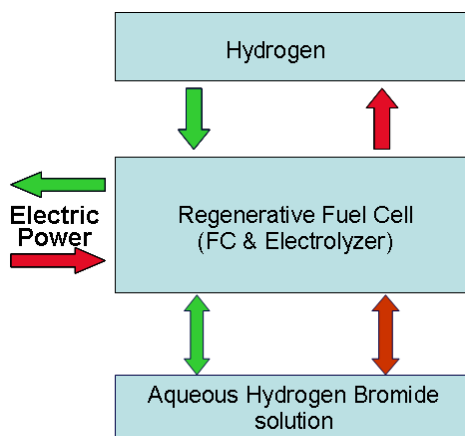
25 http://www.sandia.gov/Renewable_Energy/solarthermal/NSTTF/salt.htm

California. For example, arbitrage benefits (purchasing power at low cost times and selling at high cost high demand times) due to storage cost only one to two cents per kWh and produced a net benefit of 13.7 cents per kWh. In regions where generation capacity is tight, energy storage can avoid or offset the need for new capacity. In several scenarios for this case, storage could save from \$215 per kW to \$466 per kW in plant costs at present value. Commercial and industrial end users who qualify for time of use (TOU) pricing can benefit from storage by reducing their demand charges. Typically TOU prices vary through the day, the day of the week, and seasonally. In one example using a PG&E rate structure, a user could save \$140 per kW per year charging a storage facility at low cost times and discharging at peak times. This benefit corresponds to a present value of \$1004 per kW. These benefit examples and others such as avoided transmission and grid costs demonstrate the high payoffs possible from an efficient low cost energy storage technology.

The advancement of science for energy storage in this project was the further development of a new type of regenerative fuel cell (RFC) or flow battery using a low cost electrolyte, HBr, and a low cost, high efficiency membrane. Figure 5 shows a schematic of the device. During charging the RFC functions as an electrolysis unit where HBr in aqueous solution is converted to HBr_3 and H_2 gas, which is separated by a proprietary proton conducting membrane. The hydrogen is stored in external cylinders, while HBr_3 is stored in the original electrolyte tanks plumbed to the RFC. When the system is switched to discharge mode it functions as a fuel cell where H_2 is supplied from the cylinders and HBr_3 is converted back to HBr and electrical power is generated. The system is hermetically sealed, and there is no emission or solid waste generated during operation. The research approach was based on previous work on small 5cm^2 single test cells. These were demonstrated with output up 1.5 W/cm^2 under rather special conditions.²⁶ Their roundtrip electricity-to-electricity efficiency with HBr approached 80 percent compared to 40 percent for hydrogen/air fuel cells.⁶ This research sought to scale up cell area to 50cm^2 with specific output of 200mW/cm^2 . Cells were assembled in 10 to 15 cell stacks to produce total output of 100 to 150 W.

26 Peled, E., T.Duvdevani, A. Aharon, and A. Melman, *Electrochemical and Solid-State Letters*, 3 (12) (2000).

Figure 5: Storage Concept Block Diagram



2.6.3 Objectives

The goal of this project was to determine the feasibility of a low cost energy storage concept based on novel membrane and HBr chemistry. The researchers established the following project objectives:

1. Finalize system design. Employ Solid Works (commercial 3D CAD software) for system and component design.
2. Demonstrate good adhesion between membrane electrode assembly (MEA) components.
3. Fabricate system components, including bipolar plates, stack hardware for four systems, and MEAs for testing. Purchase PVDF electrolyte storage device.
4. Assemble and test system.
5. Demonstrate power output average of 200 mW/cm² and peak power of 500 mW/cm².
6. Demonstrate electrochemical efficiency greater than 75 percent.
7. Confirm improvement in electrochemical efficiency by +2 percent due to increase in membrane thickness.

2.6.4 Outcomes

1. The researchers performed a system and component design with Solid Works.
2. The researchers prepared an MEA by placing the hydrogen electrode and the electrolyte electrode at each side of a nano-porous proton conducting membrane (NP-PCM). After hot pressing the NP-PCM assembly at 100° C, they demonstrated intimate contact in the electro-active area and adequate adhesion.

3. The researchers fabricated hardware for a single 100 cm² cell and three test stacks of five 100 cm² cells with bi-polar plates. They fabricated MEAs in house. They did not report purchasing a PVDF electrolyte storage device.
4. The researchers assembled a complete system for testing.
5. The researchers demonstrated a power of greater than 90 W in a five cell stack with 190 mW/cm². This power average derived from 115 W on charge and 70 W on discharge.
6. The researchers demonstrated an electrochemical efficiency up to 63 percent.
7. The researchers measured electrical efficiency in variable thickness sandwiches of one, two, and three PCMs of thickness 68, 145, and 221 μ . Energy efficiency increased with thickness to 50, 56, and 58 percent, respectively.

2.6.5 Conclusions

1. The researchers met the system design objective.
2. The researchers met the objective to demonstrate good adhesion between membrane electrode assembly (MEA) components.
3. The researchers fabricated bipolar plates and stack hardware for three systems. Therefore this objective was almost met. They met the objective to fabricate MEAs for testing. Since the original objective was to construct 50 cm² cells, but the researchers actually fabricated 100 cm² cells, they exceeded this objective. They did not report performing the objective to purchase a PVDF electrolyte storage device.
4. The researchers met the objective to assemble and test one or more systems.
5. The researchers substantially met the objective to demonstrate power output average of 200 mW/cm². It was not possible, however, to assess peak power from the Final Report.
6. The researchers did not meet the objective to demonstrate electrochemical efficiency greater than 75 percent, since they measured efficiency of only 63 percent. However the researchers stated that work conducted after the grant period demonstrated 500 cm² cells with round trip energy efficiency of 80 percent. This would be a significant result.
7. The researchers exceeded the objective to improve electrochemical efficiency by +2 percent due to increase in membrane thickness.

Based on the Final Report, it appears the researchers made progress on scale-up of cell area and stack size, and they encountered no serious reliability problems due to materials issues.

2.6.6 Recommendations

The key element in this system is the proton conducting membrane. The researchers did not reveal enough details about their design and fabrication to make specific recommendations. It is clear that cell resistance was higher than desired, which reduced its efficiency. Lowering cell resistance is clearly an area to improve. The researchers also mentioned that HBr₃ leaked

through the membrane to recombine with hydrogen, producing only heat. This problem needs to be addressed.

The researchers should set up one or more cells for long term automated charge/discharge cycle testing and track secular changes in performance parameters. The objective would be to anticipate materials degradation problems as soon as possible and to identify their origin by post mortem examination so corrective action can be taken.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.6.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. A recent study analyzed 13 applications or financial benefits for California associated with the use of energy storage and their financial viability as indicated by the benefit-to-cost ratio over a 10 year storage plant useful life.²⁷ While difficult to assess with precision due to uncertainties of future requirements, the study predicted substantial cost savings. Overall, the 13 applications for storage yielded an estimated 10 year economic potential benefit of over \$13B to California. For example, arbitrage benefits (purchasing power at low cost times and selling at high cost high demand times) cost only one to two cents per kWh and produced a net benefit of 13.7 cents per kWh. Additionally, in regions where generation capacity is tight, energy storage can avoid or offset the need for new capacity. In several scenarios for this case, storage could save from \$215 per kW to \$466 per kW in plant costs at present value. Commercial and industrial end users who qualify for time-of-use (TOU) pricing

27 SANDIA, "Energy Storage Benefits and Market Analysis Handbook: A Study for the DOE Energy Storage Systems Program," Report SAND2004-6177, December 2004.
<http://prod.sandia.gov/techlib/access-control.cgi/2004/046177.pdf>

could benefit from storage by reducing demand charges. Typically TOU prices vary through the day, the day of the week, and seasonally. In one example using a PG&E rate structure, a user could save \$140 per kW per year charging a storage facility at low cost times and discharging at peak times. This benefit corresponds to a present value of \$1004 per kW. These benefit examples and others such as avoided transmission and grid costs demonstrate the high payoffs possible from an efficient low cost energy storage technology.

2.6.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.6.8.1 Marketing/Connection to the Market

The researchers have surveyed potential customers that require more than four hours of energy storage. They are also investigating regulatory changes that may be necessary to accommodate energy storage.

2.6.8.2 Engineering/Technical

Work completed after the grant period ended demonstrated 500 cm² cells with round trip energy efficiency of 80 percent. The researchers stated they could be ready for field trials in two to three years.

2.6.8.3 Legal/Contractual

The researchers performed a patent search and verified that their technology does not infringe upon existing patents. They plan to apply for patents.

2.6.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

The researchers plan to establish system safety. Other quality plans must be addressed prior to commercialization.

2.6.8.5 Production Readiness/Commercialization

The researchers appear to be taking a systematic approach to scale up to commercial size.

2.7 Fault Location in Power Distribution System with Penetration of Distributed Energy Resources

Awardee: Regents of New Mexico State University

Principal Investigator: Sukumar Brahma

2.7.1 Abstract

This research team claimed that utilities with a large number of distributed energy resources (DER) have difficulty identifying a faulted line section and the exact fault location on that section. The researchers developed a method to address this problem. The method was able to adapt to changes in the topology of the system, like connection/disconnection of line sections and/or DER units. The researchers tested the method on a simulated 60 bus, 59 line distribution system using computer simulation. They found the method worked for relatively small numbers of DERs on the system and became more robust and accurate for higher system penetration of DER. The method needs to be tested at laboratory scale and may require development of advanced sensors. If successful, it will help improve the quality of electric service in power distribution systems with high levels of DER.

Keywords: Power system protection, fault, power distribution system, distributed energy resources, fault location

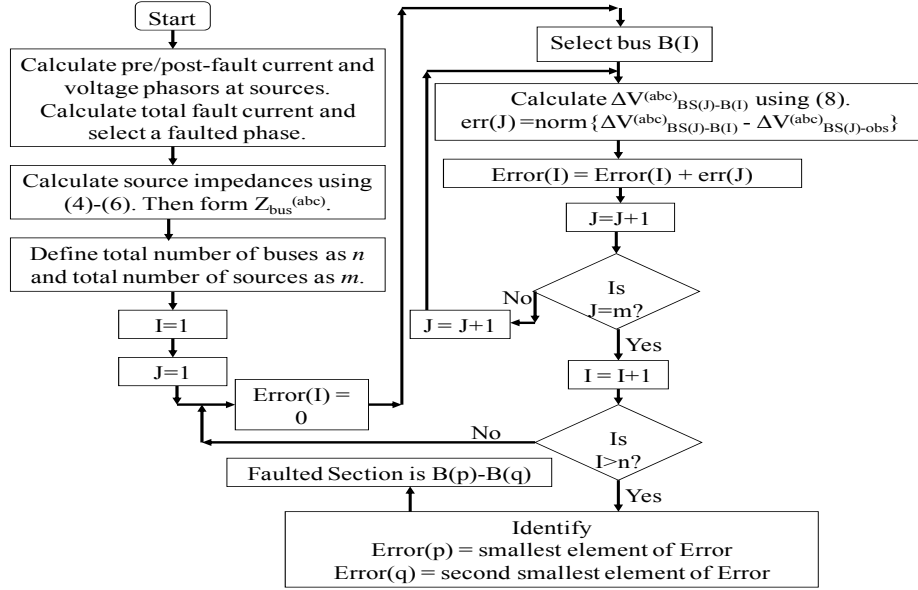
2.7.2 Introduction

Expanding the use of distributed energy resources (DER) is a primary energy policy in California. Integration of distributed energy resources with the electricity grid can result in higher efficiencies, lower capital and operating costs, and increased reliability. However, interconnection of DER within power distribution systems has technical challenges to overcome. One of these challenges is to improve fault identification and location. Inaccurate fault identification and location can result in longer outages, increased revenue loss, and decreased reliability.

Due to changes in the physical and operational nature of distribution systems, current fault detection methods are in a danger of becoming obsolete. Methods of distribution line protection and fault location reported in the literature and used in practice are based on the assumption that the power distribution system is radial, i.e., it has a single source feeding a network of distribution feeders. The coordination between protective devices can be lost due to significant penetration of DERs, rendering the protection system more prone to failure.

In this project the researchers developed a new computational method to rapidly locate where in a network system a fault exists. The researchers used PSCAD/EMTDC® software to simulate a 60 bus, 59 line distribution systems from a utility in the southeastern part of the United States. Three cases were selected: four, five, and six DER units connected to the system. Figure 6 shows the logic flow for identifying fault location within a distribution system.

Figure 6: Algorithm to Identify the Faulted Section



2.7.3 Objectives

The overall goal of this project was to determine the feasibility of accurately locating any type of fault in a distribution network containing DER units. The researchers established the following objectives:

1. Establish that a comprehensive fault location method in power distribution systems with DER is required.
2. Formulate, using network properties, a fault location method suitable for a multi-sourced unbalanced network without depending on protective devices. Demonstrate in theory that the method will be able to handle changes in the network, e.g., adding and disconnecting lines and/or DER.
3. Demonstrate by simulating 50 faults throughout the system that the method is correctly able to identify the faulted section without depending on the operation of protective devices for all the simulated cases.
4. Demonstrate by simulating 50 faults throughout the system that the method is able to locate the fault on the faulted section with ± 5 percent error for all types of faults with different fault resistances occurring at different points on the faulted section.
5. Demonstrate through simulations that Objective 3 and Objective 4 above are satisfied with different numbers of DER units connected to the distribution system and/or after some lines are added or disconnected from the distribution system.
6. Identify the extra hardware and software required and the cost to implement the method in practice.

2.7.4 Outcomes

1. The researchers completed a literature survey and found that protection systems include two components. In a traditional distribution system, the protection system is designed with the assumption that the system is radial. Ample literature is available on the second aspect, i.e., exact fault location. All the reported fault location methods assumed a radial distribution system. When DER was added, the distribution system became a multi-sourced network. The literature reported some work to address this issue, but only to the extent of identifying which section had the fault, not where the fault existed. Thus the problem of fault location in distribution systems with DER remains.
2. The researchers developed and simulated a method based on Bus Impedance Matrix to capture the system topology. This method was an application of the conventional fault analysis technique. The researchers translated the method into flow charts for easy implementation on a computer. They simulated a 60 bus, 59 line distribution system from a utility in the southeastern part of the United States using software code named PSCAD/EMTDC®. The researchers selected three cases: four, five, and six DER units connected to the system. They simulated 61 faults of different types and different fault resistances at different locations on this system. They simulated at least one fault on each line. They processed the resulting waveforms by the algorithm derived from the flowcharts. The researchers simulated the algorithm in MATLAB®.
3. The researchers found that results with four DER units representing a 6.7 percent DER penetration were satisfactory. Higher DER penetration yielded even better results. With six DER units representing a 10 percent DER penetration, the algorithm correctly identified the faulted section with less than ± 5 percent error in the fault location for all cases simulated. The researchers demonstrated correct line identification in 96.7 percent of the simulated cases even with relatively low DER penetration.
4. Correct fault location on the faulted line was achieved in 98.4 percent of the simulated cases.
5. The researchers calculated that the method worked well for randomly selected changes in the topology of the system. They did not specify the composition of the different configurations tested.
6. The researchers determined that this method can be implemented on modern computer systems. They noted the hardware required would entail sensors at all locations where DER units are connected to the system. These sensors would need to be able to provide synchronized measurements of the three-phase voltages and currents at the nodes where they are located. The researchers also noted that a communication system between each PMU and the central computer would be necessary.

2.7.5 Conclusions

The simulation results indicated the proposed method may give satisfactory results even with relatively low DER penetration. Simulations of higher DER penetration suggest the method may be more accurate at high levels of penetration. However the approach in the report has not

been fully validated using laboratory or field data. Demonstrating validity may be difficult in practical application, and simulations should include detailed models of various DER types. The question of how the phasors are calculated from time measurements is nontrivial.

The researchers met the performance objectives listed in the Statement of Work.

2.7.6 Recommendations

Since this research was based on computer simulations, there was no product development. However, field implementation of this approach would require use of costly synchronized measurement units. Therefore it is essential that such specialized units, specifically designed for the needs of distribution systems, be developed and modeled for effective utilization of this concept. Various types of DER, including energy storage devices, may present different challenges and should be characterized and modeled. The researchers should test the simulated results in laboratory scale hardware models of a real distribution network, including various types of DER. The researchers should carefully determine the potential for false positives (i.e., identifying the wrong network section) in the method and enhance the technique developed for correct isolation of fault sections.

The researchers should publish results and begin the process of dialogue with other researchers and network engineers to further develop the concept and determine what, if any, benefits this concept has compared to others. The researchers should work with developers of enhanced sensor devices to incorporate their performance characteristics into the researchers' model. They should also feed back sensor requirements of their model to the sensor manufacturers. Companies such as Schweitzer Engineering Labs and General Electric have filed recent patent applications on the related topic of fault location using synchro-phasors. The researchers should determine how these may be complementary or competing with the concept described here.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.7.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased reliability of the California electricity system. Currently 10 percent of California's energy comes from renewable energy resources with goals of achieving 33 percent by 2020, much of which is likely to be DER. Fault location is a major obstacle to integrating DER into the power distribution system while ensuring reliability.

2.7.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.7.8.1 Marketing/Connection to the Market

The concept is in early stages of development and will need to compete with other methods for fault identification and location in distribution systems having network characteristics. It is too early to begin marketing.

2.7.8.2 Engineering/Technical

Since the research was theoretical and only based on computer simulations, there was no product development. However, field implementation of this approach would require use of costly synchronized measurement units.

2.7.8.3 Legal/Contractual

The Program Administrator is not aware of any activity in this area.

2.7.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

There are no anticipated environmental or safety risks. Quality plans should include attention to identification and resolution of false positives as noted above.

2.7.8.5 Production Readiness/Commercialization

The concept is not ready for production or commercialization.

2.8 Microwave Induced Reaction of NO_x and H₂S in Dairy Digester Reciprocating Engines

Awardee: CHA Corporation

Principal Investigator: Chang Yul Cha

2.8.1 Abstract

Development of biogas resources in California is an important component of improving statewide distributed generation, increasing renewable energy, and reducing emissions of greenhouse gases. Hydrogen sulfide (H₂S) is the most significant contaminant in biogas produced by dairy farm anaerobic digesters. The sulfur in H₂S causes corrosive deposits and severe wear on combustion equipment and poisons catalysts used for post combustion NO_x treatment of exhaust gases. This project demonstrated the feasibility of an activated carbon based microwave treatment system to remove H₂S from dairy digester biogas and NO_x from engine exhaust while cost effectively meeting California emission standards for internal combustion engines. The researchers experimentally tested the adsorption and subsequent microwave reactivation of granular activated carbon (GAC) to remove contaminants. Greater than 95 percent of hydrogen sulfide was destroyed with microwave energy in the carbon bed by reacting with either NO_x or oxygen.

The researchers reacted a mixture of NO_x and sulfur dioxide with carbon using microwave energy. The GAC adsorption capacity for NO_x was 10 percent by weight and the microwave reactivation of NO_x saturated GAC was complete within five minutes. Because H₂S is not easily absorbed and retained by the activated carbon, the researchers selected GAC impregnated with copper oxide (CuO) for the integrated microwave treatment process. To reactive the saturated impregnated GAC, the researchers converted the copper sulfide to copper oxide using air and microwave energy.

The integrated microwave system consisted of two GAC fixed beds for NO_x removal and two CuO impregnated GAC beds for H₂S removal. Researchers estimated the total annualized treatment cost for a 299 horsepower internal combustion engine running on biogas at the Tollenaar Holsteins Dairy Farm at \$0.021per kWh.

Keywords: Biogas, microwave, emission control, NO_x, H₂S, SO₂, activated carbon, total annualized cost, CARB 2007 emission standards

2.8.2 Introduction

Development of biogas resources in California is an important component of improving statewide distributed generation, increasing renewable energy, and reducing emissions of greenhouse gases such as methane. Hydrogen sulfide (H₂S) is the most significant contaminant in biogas produced by dairy farm anaerobic digesters. The sulfur in H₂S causes corrosive deposits and severe wear on combustion equipment and poisons catalysts used for post combustion NO_x treatment of exhaust gases. Sulfur oxides (SO_x), formed in the combustion of fuels containing sulfur, are also a criteria pollutant. Traditional treatment methods do not

remove all H₂S from biogas, and more efficient removal methods are currently too costly. Even a small amount of H₂S in the biogas means the methane produced by anaerobic digestion cannot be economically utilized for distributed generation systems and meet California Air Resource Board (CARB) 2007 emission standards for small generators.

Cost effectively removing the biogas contaminants, either pre-combustion or post-combustion, would enable greater use of this renewable energy source while simultaneously reducing emissions of criteria pollutants and greenhouse gas emissions in California. Improving the economic performance of dairy operations in California would be a secondary benefit to all Californians.

The CHA Corporation proposed a treatment system that combined removal of H₂S from biogas with post combustion NO_x removal, shown in Figure 7. The researchers removed H₂S using CuO impregnated carbon and NO_x using non-impregnated activated carbon. They regenerated the contaminated carbons using microwave energy. They reacted the contaminants in a microwave induced oxidation reduction process to produce inert sulfur, nitrogen, and water vapor. The sulfur exited the process as an inert solid. The regenerated carbons were used to collect additional H₂S and NO_x. For small engines, the researchers used two fixed carbon beds and regenerated the carbon in place.

Figure 7: Picture of Lab Scale Microwave Reactor System



2.8.3 Objectives

The overall goal of this project was to determine the feasibility of a carbon based microwave treatment system to remove H₂S from dairy digester biogas and to remove nitrogen oxides (NO_x) from engine exhaust to cost effectively meet the CARB 2007 emission standards. Project objectives were to:

1. Create a bench scale microwave treatment system for biogas at minimum cost utilizing existing equipment.
2. Demonstrate that greater than 99 percent of NO_x and H₂S react in the mixed carbon bed when activated by microwave energy. Also, find and test an impregnated carbon for H₂S removal if the regular activated carbon is not suitable to remove 99 percent of H₂S from biogas.
3. Demonstrate that greater than 95 percent of original carbon adsorption capacity is recovered by microwave reactivation and greater than 99 percent of NO_x and H₂S are destroyed during microwave reactivation.
4. Confirm from project findings that the proposed process can be scaled up to treat NO₂ and H₂S on a 400 kilowatt (kW) engine running on dairy digester biogas.
5. Confirm from project findings that the preliminary estimate of \$0.01 per kilowatt-hour (kWh) treatment cost is supported by the laboratory analysis.

2.8.4 Outcomes

1. The researchers modified an existing microwave reactor system to conduct all of the experiments required for the investigation. They used NO_x and SO₂ analyzers that were calibrated and installed on the microwave reactor system.
2. The researchers measured H₂S removal under various NO_x and H₂S concentrations, varying from 72 percent to 99 percent as shown in Table 1. These destruction rates were accomplished with added oxygen flow.

Table 1: H₂S-NO-O₂ Destruction Experimental Data

Test (#)	Microwave Power (W)	H ₂ S Flow Rate (cc/min)	NO Flow Rate (cc/min)	O ₂ Flow Rate (cc/min)	NO/H ₂ S	H ₂ S Destruction (%)
1	300	9.5	8.7	5.8	0.9	78
2	450	11.5	12.6	5.8	1.1	80
3	600	11.5	12.9	5.8	1.1	91
4	750	11.5	12.9	5.8	1.1	93
5	300	11.5	15.4	7.5	1.3	80
6	450	11.5	16	7.5	1.4	81

7	600	11.5	16	5.8	1.4	95
8	750	11.5	16	5.8	1.4	96
9	300	11.1	15.7	5.8	1.4	82
10	450	11.5	16	5.8	1.4	84
11	300	11.5	16	0	1.4	96
12	450	11.5	16	0	1.4	99
13	600	12.5	16	0	1.3	88
14	750	11.5	16	0	1.4	94

(Nitrogen flow rate=8,498 cubic centimeters (cc)/min)

3. The researchers regenerated a saturated contaminant absorbing bed with 600W microwave energy. Weight loss data indicated that NO saturated GAC were completely regenerated. Some adsorbed NO reacted with GAC to produce nitrogen and carbon dioxide. The results also confirmed that microwave reactivation restored the original GAC adsorption capacity for NO.
4. The researchers developed process flow diagrams (PFD) and piping and instrumentation diagrams (PID) diagrams for a full scale installation.
5. The researchers calculated a per kilowatt hour cost of \$0.011 based on estimated capital costs and operation and maintenance costs. They based this cost on the process and flow analysis from this work and separate work on a 299 kW internal combustion demonstration under the CARB Innovative Clean Air Technology (ICAT) program.

2.8.5 Conclusions

1. The researchers successfully modified an existing microwave regeneration system for use in this test program.
2. The researchers successfully demonstrated that H₂S can be removed from simulated biogas at levels of 78 to 99 percent.
3. The absorbent material can be quickly and effectively regenerated.
4. The researchers provided initial design documents showing that scale-up to full size is feasible and practical.
5. The researchers showed that the economics of the system should effectively compete at a cost increment of \$0.011/kWh.

The researchers showed that the use of microwaves to regenerate H₂S/NO_x absorbents and achieve high removal effectiveness is feasible at cost effective prices.

2.8.6 Recommendations

The researchers should undertake a field demonstration at scale appropriate to the intended market, about 400 kW. During such field demonstration, the researchers should gather information necessary for and complete a process life cycle analysis. This should include evaluating options for the disposal of solid sulfur formed by the process. The researchers should also develop robust interlocks for the microwave chamber for personnel safety and sensors that will be durable in harsh environments and sensitive enough to detect breakthrough of H₂S from the sorbent bed.

The researchers should measure the loss of sorbent properties through multiple regeneration cycles and determine any loss of effectiveness due to changes in physical or chemical properties of the sorbent. They should develop operator and technician manuals based on information gained in the field demonstration. They should consider using narrow band microwave wavelengths specific to the chemical reaction that may reduce power consumption of the microwave.

The researchers should expand efforts to enter commercialization partnership(s) and increase technical marketing of the product concept, particularly to the California Dairy Association and beef feedlots.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.8.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California electricity supply system.

There are over 2,100 dairies in California with the potential to produce about 40 million cubic feet per day (ft³/day) of biogas with a potential generation capacity of 136–140 MW. Beneficial use of this resource could reduce approximately 20 million cubic feet per day of methane

emissions. By comparison, CARB has estimated emission reductions at large dairies to be approximately one million metric tons CO₂ equivalent in 2020.²⁸

The researchers estimated the undeveloped potential generation capacity using gases from California landfills, wastewater digesters, and food digesters at 600 MW. With the microwave emission control technology developed in this project, additional biogas engines could produce electricity and thermal energy from various biogas sources to reduce natural gas use throughout California.

2.8.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.8.8.1 Marketing/Connection to the Market

At the end of this project the researchers were working with Sacramento Municipal Utility District (SMUD) to conduct a field demonstration of the microwave technology. They were also working with Applied Filter Technology (AFT) to develop a near-term commercialization plan for biogas upgrading. They intended to work with AFT and SMUD to commercialize the microwave technology to remove NO_x from the exhaust of engines running on biogas.

2.8.8.2 Engineering/Technical

The researchers plan to continue engineering development.

2.8.8.3 Legal/Contractual

The researchers have obtained patents, including U.S. Patent #5,256,265 (10/26/1993), US Patent #6,187,988 B1 (2/13/2001), US Patent # 6,207,023, US Patent #6,419,799 B1 (7/16/2002).

2.8.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

These plans must be completed before commercialization.

2.8.8.5 Production Readiness/Commercialization

The product is ready for commercialization after completion of full scale field demonstration and development of manufacturing specifications.

28 http://www.arb.ca.gov/cc/scopingplan/sp_measures_implementation_timeline.pdf

2.9 Novel Adaptation of Three Way Catalyst for NO_x Reduction in Exhaust of Landfill Gas Engines

Awardee: University of California, Berkeley

Principal Investigator: Robert Dibble

2.9.1 Abstract

Using reciprocating engines that burn biogas generated from dairy manure or landfill gas to generate electricity is restricted because those engines produce too much NO_x relative to regulatory standards. These engine families are unable to take full advantage of three-way catalytic converters when burning such fuels. This project tested a three-way catalytic converter system with an important modification: an amount of fuel was injected into the exhaust stream prior to the catalytic converter. This post combustion exhaust treatment allowed the three-way catalyst to treat stoichiometric exhaust streams generally not available with biogas combustion systems. The concept also keeps the engines under warranty because the system makes no modifications to the engine. This project used both numerical modeling and small scale experimental tests to study the potential effectiveness of the approach. From these tests, researchers developed an operational system and its controls. Such a system could provide a much less expensive alternative to purchasing a new engine for biogas systems or reliance on selective catalytic reduction (SCR).

Keywords: Three-way catalytic converter, NO_x, stationary engine, landfill gas, post engine dithering, biogas engines, manure gas engines

2.9.2 Introduction

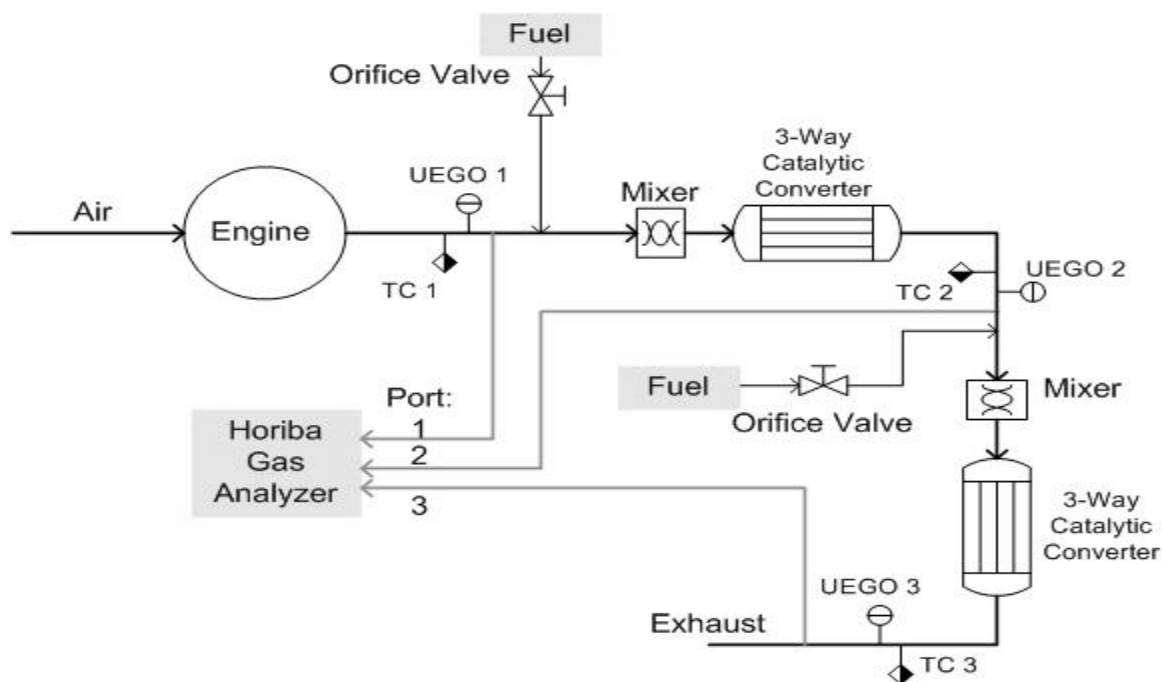
Expanded use of biogas from landfills, dairy, and sewage treatment facilities has long been a policy focus for California. However such utilization has undergone increased scrutiny because the methane produced in such facilities is a potent greenhouse gas. Biogas that emerges from dairy farms, waste water treatment plants, and landfills is about half methane and half carbon dioxide. Air Quality Management District (AQMD) standards require less NO_x than is typically produced by a stationary engine burning biogas. The current standard of 0.07 lb/MWhr reduces allowable NO_x levels dramatically, requiring advanced systems to be developed if biogas use is to continue to grow. Many of California's older facilities no longer meet current standards, and many of these older facilities face shutdown or upgrading to new equipment. One solution available is an exhaust system utilizing selective catalytic reduction (SCR) where ammonia or urea is added to exhaust upstream of a special catalyst. Another alternative is to purchase new engines and control equipment designed to operate with these fuel types.

For biogas facilities that have existing engines whose emissions are now out of compliance, the cost of SCR has poor economics. The cost of a new engine with SCR can be prohibitive. The three-way catalytic (TWC) converter has been used by the automotive industry since its introduction 1975. The TWC simultaneously controls emissions of three pollutants produced by reciprocating engines and subject to regulatory standards: carbon monoxide (CO),

hydrocarbons (HC), and nitrogen oxides (NO_x). The TWC uses a unique combination of oxidation reactions to lower CO and hydrocarbons and to reduce reactions to lower NO_x. The three-way catalytic converter is most effective when the engine runs close to the stoichiometric point (balanced fuel/air ratio). Biogas engines run lean with approximately 6 to 8 percent excess air, meaning they burn with so much air that all fuel is consumed, leaving no reducing agents to control NO_x.

This project developed and tested a TWC with a novel modification: extra fuel was injected into the lean exhaust upstream of the TWC. The researchers injected additional fuel (or air) between the biogas engine and the catalytic converter to control the stoichiometry of the exhaust passing through the catalyst, but not the engine. They coined the name post engine dithering (PED) for this process. The previously lean exhaust has fuel added to it, allowing the fuel and air to react on the catalyst and then allowing NO_x to be reduced on the catalyst. The system as set up for testing is shown in Figure 8.

Figure 8: Multi-Stage Catalytic Converter Exhaust System Test Setup



The system is a series of two identical sections containing fuel addition, a mixer, a catalytic converter, thermocouples, and oxygen sensors. TC = Thermocouple, UEGO = Universal Exhaust Gas Oxygen sensor.

2.9.3 Objectives

The goal of this project was to determine the feasibility of bringing existing stationary biogas engines into compliance with air quality standards through a novel exhaust retrofit. The objective of this project was to determine the effectiveness of the design with one three-way catalyst (TWC) converter. This project had four main objectives:

1. Demonstrate that the computer model/simulation represents reality within an error of +/- 20 percent.
2. Demonstrate feedback control and continuous monitoring of operating conditions (oxygen, temperature, NO_x).
3. Demonstrate a reduction of NO_x to levels below current standards of 0.07 lb/MWhr.
4. Demonstrate that the concept provides a more affordable alternative to purchasing a new engine for the same application.

2.9.4 Outcomes

1. The researchers compared computer simulation of the catalyst's operation with actual measurements and found as much as 200 percent error. The model results matched data for one or two gaseous species, but did not accurately correlate all of the species simultaneously.
2. The researchers developed and demonstrated a control scheme based on a feedback control system using a Universal Exhaust Gas Oxygen (UEGO) sensor downstream of the catalyst. Large amounts of unreacted methane and oxygen did not bias the sensor. The UEGO sensor was able to capture the form of the transients of the dithering process but not accurately measure the magnitude. The researchers determined that varying the amount of injected methane clearly showed an advantage in catalyst operation.
3. The researchers found that by increasing the injected amount of methane slightly, they could cause a reduction in both HC and NO_x, but if the injection amount were left constant, the HC, NO_x, and O₂ passing through the catalyst all slowly increased. Increasing the injection amount resulted in higher and higher HC after stabilization but would not stop the NO_x and O₂ from slowly increasing.
4. The researchers demonstrated that emissions of NO_x of 0.07 lb/MWhr can be achieved using a system they estimated would cost one quarter the capital cost of a new machine. The researchers did not estimate the total cost of ownership, including operation and maintenance.

2.9.5 Conclusions

1. The researchers were not able to accurately model performance. This objective was not met.
2. The researchers determined a feedback control system can be developed based on a UEGO sensor downstream of the catalyst. The UEGO sensor was able to capture the form of the transients of the dithering process but not accurately measure the magnitude. The researchers met this objective.
3. By creating a stoichiometric environment in the exhaust, particularly when dithering was applied, the researchers achieved reduction of both NO_x and HC to meet current standards. They showed reduction of NO_x to below 0.07 lb/MWhr, which satisfies current California regulations, is achievable. The researchers showed dithering to be a

technically feasible technique for improving conversion efficiency and system robustness due to the presence of multiple stoichiometric waves moving through the catalyst system simultaneously. They did not evaluate the long term effect on catalyst life of constant cycling from slightly rich to slightly lean operation. The researchers met this project objective.

4. The researchers reached the goal of less than 0.07 lb/MWhr using methane on a catalyst not specifically designed for methane fuel. Specific catalyst design may prove the system even more effective but at unknown costs. The researchers did not calculate overall cost of ownership and did not meet this project objective.

The researchers demonstrated that the concept is feasible, but they have not yet demonstrated that it is practical.

2.9.6 Recommendations

The Program Administrator recommends that the researchers:

- Improve their computer simulation model to more accurately simulate operations to improve the control scheme's algorithms.
- Test the long term durability effects of cycling chemistry (dithering) on catalyst life for either existing TWC or ones specifically designed for methane fuel use.
- Determine gas cleanup requirements for protection of the catalyst, which may be different than cleanup requirements for protection of the engine.
- Assess engine part load and ramping impacts on exhaust stream chemistry and ensure that the control system does not fall into harmonic oscillation during such operation.
- Estimate operation and maintenance needs and costs of the system and more precisely estimate capital costs for a range of engine sizes. Total system costs of ownership should be explained in ways that make it easier for engine owners to decide whether new engine purchase or retrofit using this system is most cost effective. For example, engines that are middle age are likely better candidates than those nearing end of useful life and likely to be replaced. The researchers should determine the age window and engine size range that would provide for best economics.
- Develop a comprehensive development plan, including technical requirements. The development plan should include surveying potential users to determine the age and condition distribution of engines at current biogas to electricity sites.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.9.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit of the results of this research is reduced environmental impacts of the California electricity supply, transmission, and distribution system.

A low cost approach on smaller engines for emissions compliance would make more biogas sites able to convert biogas into electric power, which would assist California in meeting its RPS and greenhouse gas reduction goals. Biogas sites include dairies, wastewater treatment plants, and landfills producing landfill gas. In the particular case of landfills, a new mandate under CARB's implementation of AB 32 requires all landfills of a certain size in California to collect landfill gas. With the PED, more of these landfills could be beneficially making use of the landfill gas. Owners of older, warranted engines and small engine owners would benefit from low cost emission reduction systems. The San Francisco Bay Area has 10 landfill sites, each generating landfill gas of about 7 MWe equivalents; thus 70 MWe could be generated in the Bay Area. As the Bay Area is about one-fourth the population of the State of California, the benefit is perhaps 280 MWe. The ability of smaller landfills throughout the state to use the technology would increase this number. By way of comparison, this represents about 2 percent of the 2020 renewable portfolio standard requirement. It also represents about 5 percent of the GHG reduction requirements in AB 32 when the higher greenhouse forcing strength of methane compared to CO₂ is considered. These numbers and percentages would increase to the extent that dairies and wastewater treatment facilities were able to make use of the technology. It is unlikely that all landfills, dairies, and wastewater treatment facilities would be able to use the technology, since engine fleet vintages vary widely and many might be due for replacement.

2.9.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.9.8.1 Marketing/Connection to the Market

The researchers have not focused on the market. They do not have a commercial partner willing to take the technology to market. The researchers are unclear on the market need. Is the need for green methane or for green electricity? They have not developed a business plan.

2.9.8.2 Engineering/Technical

The researchers have not yet developed technical or engineering requirements other than the need for improved oxygen sensors and methane friendly three-way catalysts. They speculate that at least two years of further development are required.

2.9.8.3 Legal/Contractual

The researchers have not applied for a patent nor have they entered into commercialization agreements. The researchers have not conducted a patent search to identify possible patent conflicts.

2.9.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

There are no known environmental or safety risks associated with this concept. Quality assurance plans will need to be developed that consider long term dithering on catalyst lifetime. The system concept will need to be certified by air quality regulators to meet environmental standards, likely for each engine class or family.

2.9.8.5 Production Readiness/Commercialization

The concept is not yet ready for production or commercialization. If the technology is successful, the University could license it to one or more companies.

2.10 Pomace and Woody Biomass for Renewable Biomass Power: Technical and Economic Feasibility

Awardee: Evan Hughes

Principal Investigator: Evan Hughes

2.10.1 Abstract

The goal of this project was to prove feasible a method to process wet food wastes and woody biomass wastes via a caustic pulping process. The researchers anticipated that such a process could bring into commercial practice biomass power and biomass combined heat and power (CHP) at ~10 MW scale to replace natural gas use in food, forest products, and pulp/paper

industries. This could launch biomass gasification and anaerobic digestion (AD) for approximately 300 MW of new biomass power generating capacity annually for California. The target waste stream was pomace, the very wet waste product generated by wineries as a result of pressing grapes, and woody wastes generated through vine pruning and crop management. AD of winery wastes has been attempted unsuccessfully by other researchers who have found the lignin content of the waste to hinder the digestion process. The researchers proposed to incorporate a lignin separation process into the waste treatment system to optimize the energy recovery potential from the AD process. They tested alkali pretreatment on a variety of waste streams, including flax straw, pomace, woody waste, and combinations of pomace and woody waste. The pretreatment process proved successful in increasing methane yield by 80 percent through AD for flax straw. However, results for various winery waste combinations ranged from an improvement of 20 percent to a degradation of 20 percent, possibly due to unintended extraction of carbohydrates. The researchers assumed that the pretreatment process could be improved and optimized through additional research such that methane yields could approach 400 milliliter per gram of volatile solid (mL/gVS) for the target waste streams. Should this level of production be realized, a 250 ton per day (tpd) capacity plant could generate approximately 13 MW net power with a generation cost of approximately 13 cents per kWh.

Keywords: Anaerobic digestion, pomace, wood, biomass, power, heat, cellulose, lignin, alkali, pulp

2.10.2 Introduction

California wineries produce nearly 90 percent of all wine produced in the United States, with the number of wineries approaching 3,000. On average wineries produce 800,000 tons of pomace annually for every 50,000 cases of wine produced. Pomace, comprised of the wet solids remaining after the grape pressing process, and woody waste from vine pruning are presently financial burdens to wineries because they must pay for their disposal. The researchers proposed to turn this burden into an asset through anaerobic digestion (AD) of the waste and extraction of methane to fuel a biomass combined heat and power (CHP) plant. Energy derived from the waste and produced by the biomass plant would provide an environmentally friendly alternative to fossil fuel driven energy sources otherwise used by wineries.

Bacterial processes occurring through AD are highly susceptible to toxins such as lignins contained within winery waste. For this reason, AD of winery waste has been ineffective to date. The researchers incorporated an innovative lignin separation process upstream of the AD power generation plant. Figure 9 shows a conceptual configuration of the winery waste treatment plant. Several byproducts of the process, including lignin and cellulose, could be extracted and sold to provide additional revenue and recycling benefits. The researchers planned to leverage an existing pilot AD plant constructed by researchers at the University of California Davis to pilot test a one ton per day (tpd) capacity pomace and woody waste AD biogas plant. The modular approach shown in Figure 10 would be employed to provide pretreatment of the waste stream prior to AD. This plant would be capable of processing pomace, woody waste, and combinations of the two wastes.

The researchers performed laboratory testing for the three treatment steps shown in Figure 10 for waste streams including flax straw, pomace, woody waste, and a combination of pomace and woody waste. They found the lignin separation process increased methane production by 80 percent for flax straw as compared to that of the black liquor which bypassed the lignin separation process. Results for pomace, woody waste, and combinations were not as favorable, with results ranging from an increase in methane production of about 20 percent to a decline in production of about 20 percent. The researchers theorized that the lignin separation process removed carbohydrates which would have otherwise been available for digestion. Although laboratory experiments on winery wastes could not emulate the favorable response found in flax straw, the researchers assumed that process optimization would allow an 80 percent improvement in methane recovery through lignin separation. Consequently, the researchers derived energy production costs and benefits using significant correction factors applied to laboratory results for winery wastes based on the results for flax straw.

Should this technology be implemented, the researchers estimated that biomass power production could exceed 300 MW per year in California. Additionally, the biomass power production would provide an alternative to fossil fuel electricity, providing a 1.13 M metric ton per year CO₂ reduction within California. Although this technology would provide an alternative to fossil fuel electric generation, capital costs associated with the biomass plant would be prohibitive.

Figure 9: Renewable Energy Products from Winery Waste

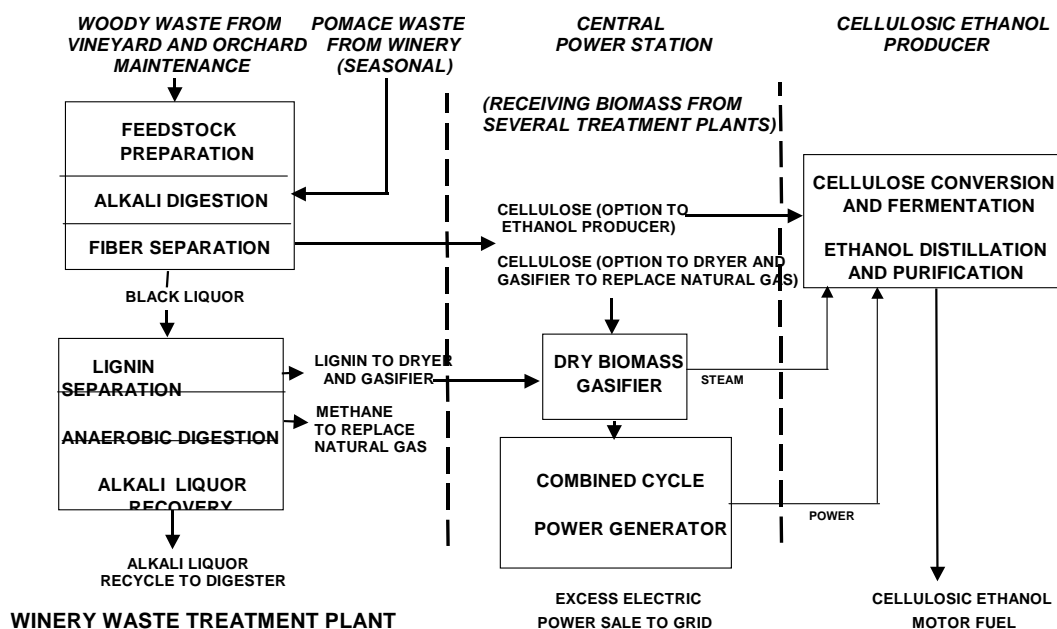
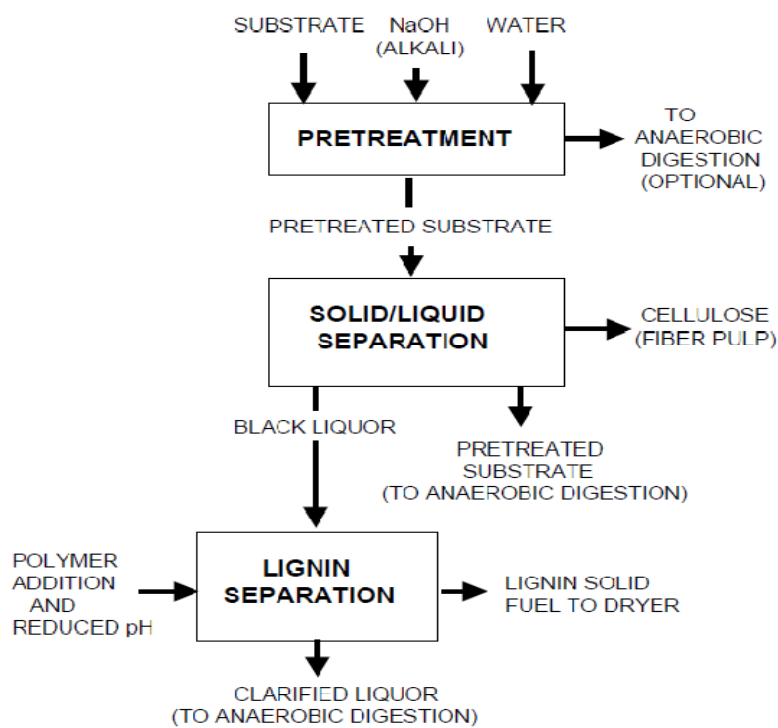


Figure 10: Flowstream Diagram of Pretreatment Steps



2.10.3 Objectives

The goal of this project was to prove the feasibility of a method to process wet food wastes and woody biomass wastes, via a caustic pulping process, into a fuel for commercial biomass power and CHP at ~10 MWe scale. The resulting energy would replace natural gas use in food, forest products, and pulp/paper industries. The researchers estimated a potential of 300 MW of biomass power for California using this method. The benefit to California electricity rate payers would be a renewable CO₂ neutral source of electricity at costs about the same as they would be if natural gas could be obtained at \$6.00 MMBtu. The researchers established the following project objectives:

1. Confirm the expected advantage of lignin separation: 30 percent higher biogas production when lignin is removed by the proposed pretreatment.
2. Achieve 25 percent better economics based on actual measurements of biogas production and process stream compositions.
3. Produce a demonstration pilot plant facility design that will test a cost effective outcome for winery operators and for other related biomass energy applications.
4. Evaluate commercial feasibility based on estimates for commercial facility capital costs, with amortization of investment included in profitability projections. Targets: \$8 MMBtu natural gas equivalent; 12 cents per kWh electricity equiv.; 300 MW potential in California.

5. Determine from project findings an estimated life cycle cost of renewable energy from winery waste to be supported at competitive market prices. The market price goals are as above: \$8.00 MMBtu natural gas and 12 cents per kWh retail electricity.

2.10.4 Outcomes

1. The investigators compared the anaerobic digestion (AD) biogas output for both clarified liquor (lignins removed) and black liquor (lignins not removed) for three different input materials: flax straw, a 50/50 mixture of wood and pomace, and wood. In the case of flax straw, removal of the lignins resulted in an 80–100 percent increase in methane production, although actual yields were not documented. Methane production upon lignin removal actually decreased for the wood/pomace mixture. The clarified liquor produced a yield of 320 milliliter per gram of volatile solid (mL/gVS) compared to the black liquor yield of 600 mL/gVS at the seven day point, a 47 percent decrease in yield. The researchers estimated that a significant fraction of the non-lignin biomass was inadvertently extracted along with the lignins in the clarification process. Consequently they applied a correction factor to the laboratory results to estimate the methane production in hypothetical clarified liquor that had no carbohydrate loss. Even after correcting the laboratory results, the researchers estimated that the yield would decrease by 20 percent by removal of lignins for the wood/pomace mixture. Laboratory results for the wood similarly indicated a decrease in methane production with a yield of 390 mL/gVS for black liquor compared to 320 mL/gVS for clarified liquor, an 18 percent decrease. However, the researchers applied a correction to the laboratory results as for the wood/pomace mixture, resulting in a 20 percent increase in methane production. They did not address the original objective to confirm lignin separation of greater than 80 percent of toxins.
2. The researchers used results from Objective 1 to calculate the electricity cost resulting from an AD power system. They used the baseline cost of 12 cents per kWh for electricity supply to a winery for comparative purposes. The researchers estimated that energy costs for an aerobic digestion power system would be approximately 17, 13, and 10 cents per kWh for facility capacities of 45, 250, and 665 tpd, respectively. The largest scale facility resulted in a 17 percent improvement over the baseline. The researchers performed calculations assuming that 400 mL/gVS could be produced for clarified liquor. This level of production assumed that the process could be optimized and included an 80 percent correction factor based on results from flax straw testing.
3. The researchers designed a pilot plant facility capable of processing one tpd of pomace and woody biomass. The pilot plant would leverage an existing University of California Davis pilot plant by incorporating upstream modules capable of input pretreatment and clarification. Researchers estimated costs for a one year pilot program would be \$350,000.
4. The researchers used a 400 mL/gram biogas production rate to calculate the resultant electricity cost at a 250 tpd capacity plant. They evaluated several scenarios, ranging from a pomace only processing plant to a pulping power AD wood and pomace

processing plant. They calculated total power output in the range of 5 to 13.5 MW, depending on whether cellulose went to AD and the combination of processing and power cycles employed. The best case 13 MW plant resulted in an energy cost of 13.5 cents per kWh, higher than the targeted value of 12 cents per kWh. Using economy of scale, the researchers estimated that a larger 665 tpd capacity plant would have a 10 cent per kWh energy cost. The researchers based their 300 MW electricity supply potential on the utilization of 300,000 tons per year of pomace generation and 80 percent plant capacity. They derived the 300 MW from 20 plants with a 250 tpd capacity generating 15 MW each or 10 plants with a 500 tpd capacity generating 30 MW each. They did not give details of this assumed market penetration rate.

5. The researchers addressed key life cycle assessment issues, but they did not complete an original life cycle analysis. They estimated power generation as 2.5 MW per year assuming a 45 tpd pomace biomass input and operation at 89 percent capacity. Addition of woody wastes to the input stream with a combined total of 250 tpd biomass would increase power output to 15 MW per year. Costs for the pomace only and combined plants would be approximately \$11M and \$60M, respectively. Plant costs would be offset by a reduction in pomace disposal costs of \$0.6 M per year. Additional benefits would include a 1.13 M metric ton per year CO₂ reduction within California. Power generation from the AD plant would be approximately \$9 MWh more than conventional power generation, but the additional cost would be offset by an equivalent \$15 per metric ton CO₂ cost savings for the fossil carbon emission reduction.

2.10.5 Conclusions

1. The researchers did not meet the objective to confirm a 30 percent higher biogas production when lignin was removed by the proposed treatment. They did not present the basis for selecting the correction factors applied, and the factors appeared to be very subjective. The impact of the correction factor was quite significant. In the case of woody biomass, laboratory results indicating an 18 percent decrease in methane production were corrected to instead show a 20 percent increase in methane production. Without laboratory documentation to validate such a significant correction factor, its validity is questionable. Two of the three tests were performed on materials relevant to this study, pomace and woody biomass. In these two cases, actual results demonstrated that lignin separation could either improve or deter methane production by 20 percent. However the researchers relied on the results of the flax straw test which showed a favorable 80 percent improvement, even though flax straw is not part of the anticipated waste stream. Arguably, the separation process could be optimized and improved to minimize the amount of carbohydrate loss during the clarification process. However, the statement that “an 80to 100 percent increase in methane yield from AD” would result was not proven experimentally for the waste stream targeted for the proposed treatment.
2. The researchers did not meet the objective to achieve a 25 percent improvement in electricity cost through the use of AD power production, but instead showed a 17

percent improvement for a large scale facility. Although the calculated results nearly reached the 25 percent goal, they relied heavily on unconservative assumptions that require process improvement and methane production well beyond the limits shown in the laboratory for pomace and woody biomass. The researchers did not present resultant energy costs using actual laboratory data for pomace and woody biomass.

3. The researchers met the objective to design and estimate costs for a pilot plant facility. The researchers recognized “the need to verify the performance estimated from the laboratory testing by more tests and with integration of equipment capable of customizing and optimizing pretreatment of several feedstocks, so as to achieve the 400 mL/gVS yield, or close to it, from biomass sources.” Although they included this verification as part of the field testing of the pilot plant, construction of the plant appears premature and may prove costly should actual performance emulate laboratory results from the present study.
4. The researchers were able to meet the objective in the case of a larger 625 tpd capacity plant, with an energy cost of 10 cents per kWh. However the 250 tpd capacity plant exceeded the target of 12 cents per kWh with a calculated energy cost of 13.5 cents per kWh. The 300 MW potential appears highly obtainable and perhaps overly conservative. According to the Wine Institute there were 2,972 wineries in California in 2009.²⁹ Cooke provides a breakdown of wineries by production capacity which can be used to extract approximate percentages of wineries operating at various capacities.³⁰ Storm notes that wineries producing 50,000 cases of wine per year produce 800,000 pounds per year of pomace waste.³¹ These statistics, along with data obtained in the researchers’ report, were compiled to create Table 2. With an assumed 10 percent market penetration, the potential energy benefit to California could range from 1400 to 2200 MW for plant capacities ranging from 250 to 625 tons per year, far exceeding the 300 MW target objective.
5. The researchers did not meet the objective to estimate the life cycle cost of renewable energy from winery waste at competitive market prices. The significant capital cost of the biomass plant does not result in reduced energy cost. Instead, the benefit is primarily found in eliminating the relatively minimal cost for disposal of pomace waste and in reducing carbon emissions. The researchers did not elaborate on revenues that might be gained from the sale of components captured during clarification, but these byproduct

²⁹ Wine Institute, "Number of California Wineries," April, 2010.
<http://www.wineinstitute.org/resources/statistics/article124>

³⁰ Cooke, George M. and Edward P. Vilas, "California Wineries: Growth and Change in a Dynamic Industry," *California Agriculture* 43(2):4-6 (March-April 1989) DOI: 10.3733/ca.v043n02p4.
<http://californiaagriculture.ucanr.org/issue.cfm?volume=43&issue=2>

³¹ Storm, David R., *Winery Utilities: Planning, Design and Operation*. (New York: 1997), p. 371.

revenues are likely not significant enough to provide economic justification for the plant capital costs.

Table 2: Pomace Waste and Power Production Potential as a Function of Capacity

Wine production in thousand gallons per year	74	119	186
Wine production in # of Cases	31,250	50,000	78,125
Pounds per year pomace waste (Storm, 1997)	500,000	800,000	1,250,000
Tons per year pomace waste	250	400	625
tpd pomace waste	0.7	1.1	1.7
Approximate plant yield in MW	13.5	21.6	33.75
% of CA wineries >= this capacity (Cooke, 1989)	35%	27%	22%
# of CA wineries >= this capacity	1040	802	654
Approximate MW potential assuming 10% market penetration	1404	1733	2207

2.10.6 Recommendations

The researchers were unable to achieve their project goal to prove feasibility of a pomace and woody biomass fed power plant. They were unable to demonstrate that power could be produced more economically than commercially available electrical power and were unable to justify the large capital costs associated with the biomass plant. Power production costs of the biomass plant were less than fossil fuel electrical generation only as the plant size increased to a 625 tpd scale. However, with only approximately 650 wineries in the California having this capacity or greater, a 10 percent market penetration would suggest that the technology might be implemented at only 65 locations. Given the lack of broad applicability and the valuable and environmentally friendly alternatives to disposal of pomace waste, including composting, it is unlikely that the costs would be justified by the benefits.

As part of continued development of this technology, the Program Administrator recommends that the following tasks be completed:

1. Conduct additional testing on pomace and woody biomass samples to optimize the clarification process and validate the 80 percent improvement and 400 mL/gVS production assumptions.
2. Perform thorough life cycle cost analysis to identify additional cost savings and benefits for the proposed technology, for example, through separation byproduct sales.

2.10.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. Objectives 4 and 5 addressed benefits to California, including a 300 MW generation potential which would be used to replace fossil fuel power generation, resulting in a 1.13 M metric ton per year CO₂ emission reduction within California. Other benefits include reduction in waste material which might otherwise fill landfills and extraction and recycling of materials which might be of value.

2.10.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.10.8.1 *Marketing/Connection to the Market*

The researchers have not yet performed a market analysis. This technology would provide an alternate source of energy where fossil fuel electricity is presently provided.

2.10.8.2 *Engineering/Technical*

The researchers intend to continue development and will continue testing for biogas yield during experiments with a one tpd pilot plant.

2.10.8.3 *Legal/Contractual*

The researchers have not applied for or secured patents. However Bountiful Applied Research, a project partner, has patented the lignin separation process.

2.10.8.4 *Environmental, Safety, Risk Assessments/ Quality Plans*

Because of technology immaturity, these plans have not been developed.

2.10.8.5 *Production Readiness/Commercialization*

The researchers plan to pursue commercialization but have not identified distributors who wish to market the proposed technology.

2.11 Biogas Generation from Algae Biomass Harvested at Wastewater Treatment Facilities

Awardee: California Polytechnic State University Corporation

Principal Investigator: Tryg Lundquist

2.11.1 Abstract

Wastewater treatment pond grown microalgae are a potentially important biomass for biofuel production. However most of the 7,000 wastewater treatment pond systems in the United States do not use algae harvesting. Those that do harvest algae typically return the biomass to the ponds, where it decomposes on the pond floor. The decomposition process releases methane into the atmosphere and degrades the water quality. As an alternate, the algae biomass could be processed in anaerobic digesters. Algae typically yield less methane than wastewater sludge in digestion. In this project the researchers evaluated digestion of wastewater sludge together with treatment pond algae.

This research may assist planning for full scale algae digestion at large pond facilities, but further work is needed. The independent variables evaluated included algae/sludge ratio in the digester feed (100 percent to 0 percent), organic loading rate (OLR), and hydraulic residence time. The main dependent variables tested were methane yield, volumetric methane production, and the ability to dewater the digester effluents. The digestion was stable with robust pH at all algae/sludge ratios tested with OLRs up to 4 g volatile solids loaded per liter digester per day (g VS/L-d) at a 20 day retention period (HRT). A control digester that fed sludge exclusively had higher yield and production, as would be expected. Yield results were inversely proportional to the algae content. Extending HRT to 40 days did not increase methane yield. An engineering model estimated heating requirements and net electricity production for a full scale algae digester. Despite the lower methane production of algae digestion, heat recovered from cogeneration could be more than sufficient to maintain mesophilic temperature in the algae digestion tank, even in cold climates. The project researchers projected gross electricity generation to be 0.8 kWh/kg algal volatile solids digested.

Keywords: Anaerobic digestion, algae, algal biomass, wastewater treatment

2.11.2 Introduction

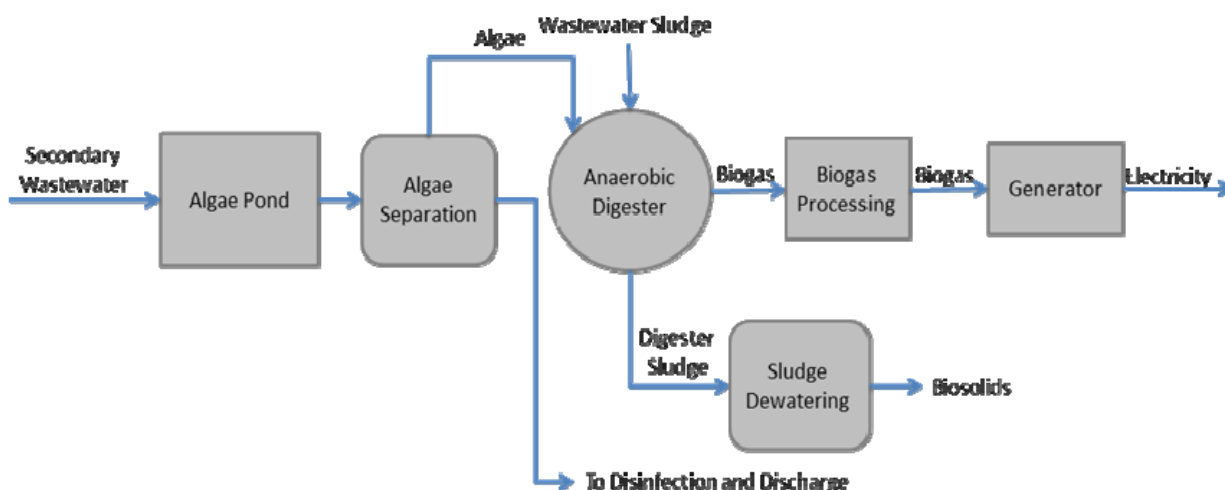
Wastewater treatment pond grown microalgae are a potentially important biomass for biofuel production. However most of the 7,000 wastewater treatment pond systems in the United States do not use algae harvesting. Those which do use algae harvesting typically return the biomass to the ponds where it decomposes on the pond floor, releasing methane into the atmosphere and degrading the water quality. Instead, the algae biomass could be processed in anaerobic digesters. Algae typically yield less methane than wastewater sludge.

Wastewater treatment pond systems generally use less electricity and are less complex than common mechanical wastewater treatment systems such as activated sludge. Lower electricity usage is achieved, in part, through the photosynthetic production of oxygen by algae, which can

offset the need for mechanical aeration. At several large California wastewater pond systems (Sunnyvale, Napa, Modesto, and Stockton) these algae are removed from the final effluent prior to water discharge. The algal biomass is not anaerobically digested for biogas production, as is often done with sludge at mechanical wastewater plants. Instead, the algal biomass is disposed of in the ponds, representing a loss of biogas production potential and an increased organic matter and nutrient load on the treatment system. If the biomass degrades anaerobically in the pond, an increase in atmospheric methane emissions occurs.

In this project researchers evaluated the joint digestion of wastewater sludge and algae to increase the effective use of biomass material in the production of biogas. The produced biogas was used to produce electricity and heat, aiding the process and producing excess electricity available for sale. Figure 11 provides a schematic of the overall process.

Figure 11: Schematic of a Wastewater Treatment Pond Process Modified to Include Anaerobic Digestion of the Algae



2.11.3 Objectives

The goal of this project was to determine the feasibility and performance metrics for algae digestion with wastewater sludge as a co-substrate. The researchers established the following project objectives:

1. Achieve equal CH₄ yield for digesters with high (4 g/L-N) and low (1 g/L-N) total ammonia N concentrations through adaptation.
2. Identify feedstocks with higher than 15:1 C to N ratios near existing, larger than 100 acre wastewater pond systems and the Imperial Valley power plant site; with pulverized feedstocks available at less than \$15/ton; and with sufficient quantities to allow for more than 500 kW_{equivalent} for 10 years.

3. Achieve methane yields greater than 1.6 L/L_{digester}/day and greater than 0.4 L/g loaded. Methane yield should increase more than two times based only on the additional carbon.
4. Test whether digested biomass dewateres 15 percent faster than conventional wastewater sludge. Demonstrate that digested solids contain more than 4 percent total nitrogen (N), 3 percent total phosphorous (P), and 0.5 percent potassium (K).
5. Develop curves of methane yield vs. entrained air volume for two digester loading rates.
6. Demonstrate that the greenhouse gas benefit is more than 130 kg CO₂equivalent per person per year, and the internal rate of return for algae co-digestion at wastewater plants is more than 8 percent, given energy and fertilizer offset/revenue.
7. Facilitate rapid implementation of algae co-digestion through information transfer.

2.11.4 Outcomes

Project outcomes are presented below as they correspond to the original proposed objectives.

1. The researchers measured the methane yield as a function of overall organic loading rate (OLR) and total ammonia concentrations. However, because the sludge co-substrate had a C to N ratio similar to algae, total ammonia concentrations correlated with overall organic loading rate (OLR) regardless of co-substrate ratios in the feed. The researchers tested throughout a range of ammonia concentration of 3.6 g/L-N (in the most heavily loaded digesters) and 0.9 g/L-N (the lowest concentrations). OLR also correlated with methane yield.
2. The researchers investigated the availability of high carbon, low cost substrates suitable for anaerobic digestion in the areas around the California cities of Sunnyvale, Napa, Imperial Valley, and San Luis Obispo. The researchers did not locate suitable substrates in sufficient quantities. They then chose wastewater sludge as the co-substrate to study.
3. The researchers measured the methane productivity at 0.52 L CH₄/L_{digester} per day in each of two duplicate digesters for the 100 percent algae digesters loaded at 2 g volatile solids/liter of digester. The test had a 20 day residence time at 37.5° C. For a loading of 4 g volatile solids/liter, the researchers measured productivity of 0.85 to 0.95 L/L per day.
4. The researchers determined that digested algae biomass could be dewatered to an equivalent or higher solids concentration than conventional wastewater sludge. The effluent from digesters fed 100 percent algae reached an average solids concentration of 10 to 13 percent after dewatering, with a cationic polymer dose of 5 g/kg test substance.
5. The researchers did not develop curves of methane yield vs. entrained air volume.
6. The researchers estimated avoided greenhouse gas (GHG) emissions based on displaced electricity and avoidance of methane emissions from algae being disposed in the ponds. For the net electricity production estimate, the researchers assumed a wastewater pond facility that had existing under-loaded anaerobic digesters. The researchers ran the

model assuming the digester operating in sludge only mode without algae digestion. They then modified the model to include the addition of the algae to the digester feed, which decreased the HRT and increased the OLR and the biogas production. They estimated net electricity production would increase 3,700 kWh per day with algae co-digestion, equivalent to a savings in electricity purchase of \$225 per day at 0.06 \$/kWh.

7. The researchers developed information about co-substrate availability, allowable organic loading rate, and hydraulic residence time that could guide operators exploring full-scale algae digestion.

2.11.5 Conclusions

1. The most heavily loaded digesters reached concentrations of 3.6 g/L-N rather than 4 g/L-N, and the lowest concentrations were 0.9 g/L-N. OLR also correlated with methane yield. Thus the effect of ammonia concentration on methane yield was obscured by the co-correlation of OLR vs. ammonia and OLR vs. methane yield. The higher yield value was likely due to the higher solids concentration in the feed needed to achieve the higher loading. Methane yield values for 100 percent algae digesters ranged from 0.21 L to 0.26 L CH₄/g volatile solids introduced. These values were lower than the project objective because high carbon substrates were not loaded. OLR excursions over 4 g/L per day led to culture instability. The 100 percent algae digester biogas contained 69 to 76 percent methane, matching the expectations of the proposal. The researchers did not quite achieve this objective.
2. The researchers did not achieve this objective. Substituting wastewater sludge for algae biomass in co-digestion raises significant concerns about the project's applicability because of algae's fundamentally different behavior in digesters. The sludge used did have similar enough chemical properties to provide useful information. Physical properties need further research.
3. Methane yields achieved did not meet the project objectives since no high carbon substrate resulted to adjust and modify the C to N ratios.
4. The researchers demonstrated dewatering properties of algae biomass digestate that are comparable to or better than wastewater sludge digestate. The researchers achieved this objective.
5. The researchers did not achieve this objective, although for some treatment facilities it may be moot. For example, during the course of the project the researchers learned the Sunnyvale facility will use a gravity thickener to concentrate and de-gas the dissolved air flotation (DAF) float prior to digestion.
6. The estimated net increase in electricity production could displace electricity production from fossil fuels, providing a GHG benefit. Assuming wastewater is generated at 0.38 m³/person-d, the 135,000 m³/d hypothetical pond facility could treat the wastewater of 355,000 persons. Thus the CO₂ displacement due to additional methane production would be 2.3 kg/person-year, assuming national averages for CO₂/kWh. This amount

would be less in California given the lower average CO₂/kWh. For the business as usual case where algae float is disposed of in the ponds, additional GHG emissions would occur from the ponds. The projected methane emissions of 1,481 m³/day is equivalent to 726 kg/day CO_{2eq}. Over the course of a year, this emission is equal to 0.75 kg/person-year. Thus the combined GHG displacement from diversion of algae float from the ponds into digesters is about 3.0 kg/person-yr of CO₂ equivalents. The total reduction of about 3 kg/person-year is much less than the objective of 130 kg/person-year. The reasons for the low impacts are that no high carbon co-substrate was identified and the methane yield from the algae biomass was modest. The researchers did not meet this objective.

7. Information provided by the researchers is of use to treatment facilities contemplating co-digestion, but it is insufficient to their needs for final decision making.

Overall, the researchers did not demonstrate the feasibility and performance metrics for algae digestion with wastewater sludge as a co-substrate. This technology is not ready for larger scale demonstration. One barrier to efficient algae digestion is the resistance of algal cells to anaerobic degradation. Some form of cell wall disruption may be necessary to overcome this barrier.

2.11.6 Recommendations

The researchers should investigate the performance of algae biomass as a co-substrate, including needs for cell wall disruption, in an actual demonstration. Due to the apparently recalcitrant nature of algal cell walls, a particularly valuable area for future research would be cell disruption prior to digestion to achieve greater volatile solids destruction and methane production. The researchers should investigate digester performance as a function of salinity and incoming pH and determine nutrient levels in digestate.

Once researchers demonstrate algae cell disruption and subsequent co-digestion, they should develop engineering plans for integrated facility equipment sizing and operation. Several devices that may prove useful for the more fibrous algae cells are commercially available for disruption of bacterial sludges at wastewater treatment plants. Some use a French press type mechanism which disrupts cells as they are forced through narrow nozzles at high pressure. Others use gas decompression in which nitrogen gas is dissolved at high pressure into cells followed by sudden pressure release. Pilot scale research is needed to allow a more accurate assessment of parasitic energy use by the disruption equipment and a determination of whether improved methane yields justify disruption use.

The researchers should survey local governments for environmental and safety requirements for systems as described.

2.11.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system

- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California.

The laboratory research conducted under this project is most immediately of value to the city of Sunnyvale as it continues to plan for full scale demonstration of anaerobic digestion of algae biomass. Digestion of the city's average daily algae production could generate 3,700 kWh per day without the use of cell disruption. This renewable power would offset \$82,000 per year of electricity at \$0.06/kWh. It is unknown how large the benefit might be with algae cell disruption since that was not accomplished in the current project. In the longer term other pond facilities, such as those operated by the cities of Stockton, Modesto, and Napa, could also adopt algae digestion if Sunnyvale is successful and the economics are positive for that facility.

2.11.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.11.8.1 Marketing/Connection to the Market

The researchers intend to offer technical assistance to municipalities considering algae digestion to increase their renewable fuel production.

2.11.8.2 Engineering/Technical

The researchers plan to continue the engineering development and demonstration at the city of Sunnyvale. Additional funding and regulatory approval are needed for the next phase of work.

2.11.8.3 Legal/Contractual

The researchers intend to make the information gained in this project available to the public without license.

2.11.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

This technology may be subject to location specific permitting under local environmental or safety regulations.

2.11.8.5 *Production Readiness/Commercialization*

The technology is not ready for full-scale demonstration, at least until algae biomass cell disruption and co-digestion are demonstrated and performance metrics established.

2.12 A Reliable Low Cost Power Electronics Interface for Renewable Energy Systems Using a Single DSP Controller

Awardee: University of Houston

Principal Investigator: Wajiha Shireen

2.12.1 Abstract

Renewable energy sources such as photovoltaic arrays and fuel cells generate direct current (DC), whereas the electric grid and end-use equipment use alternating current (AC). In addition, DC voltage produced by renewable sources may vary considerably and is known to have slow response times. Hence there is a need for power conversion and energy storage in any system that opts to use renewable sources of energy. In most cases the associated power electronics interface includes two converter stages, a DC to DC converter (DC-DC) and a DC to AC converter (inverter). The DC-DC converter usually has the additional task of harvesting the energy from the initial energy generator. This means that the optimum voltage and current must be maintained in order to deliver maximum power, since driving forces change over time. In addition to the power converter stages, systems include intermediate energy storage stages such as batteries or DC link capacitors to improve dynamics. Performance, efficiency, and cost of power converters are important considerations for the commercialization of renewable power sources.

This project proposed a reliable and low cost power electronics interface for renewable energy systems using a single Digital Signal Processor controller. Its goal was to integrate the DC-DC converter control and inverter control by utilizing a single low cost, fixed point Digital Signal Processor (DSP controller); reduce the size of the DC link capacitor by using a modified pulse width modulation (PWM) technique for inverter control; and incorporate a new fast converging maximum power point tracking control (MPPT) method in the DC-DC converter stage to draw the maximum power from the PV source under all operating conditions.

Keywords: Photovoltaic, DSP control, inverter, renewable energy, DC link capacitor

2.12.2 Introduction

This project addressed the need to reduce the cost of converter electronics that connect renewable energy sources to homes or the grid. The researchers used numeric control schemes based on a single digital signal processor (DSP) to implement sophisticated algorithms in both the DC-DC and the DC-AC converters. They sought to demonstrate that a smaller and more reliable capacitor can be used for the DC link capacitor because of the control of the DC-AC inverter that is possible with the high speed DSP. Renewable energy systems must address the

key issues of cost, reliability, and energy efficiency. In photovoltaic and fuel cell energy systems a significant part of the power system cost is due to the power electronics technology.

Researchers were actively seeking converter topologies and control methods to meet the requirements of efficient but low cost power electronics for renewable energy systems. This project proposed a two stage converter suitable for a wide input range fuel cell power or photovoltaic conversion. The approach taken for this project focused on simultaneous control of the first stage (DC-DC converter) and the second stage (DC-AC inverter) with a single digital signal processor. It used a fast converging Maximum Power Point (MPP) tracking method in the DC-DC converter stage and a modified pulse width modulation (PWM) technique for single phase inverter control as shown in Figure 12. The size of the DC link capacitor could be reduced because of the sophisticated inverter control. Figure 13 is a photograph of the prototype of the proposed system.

Figure 12: Block Diagram of the Proposed Power Electronics Interface

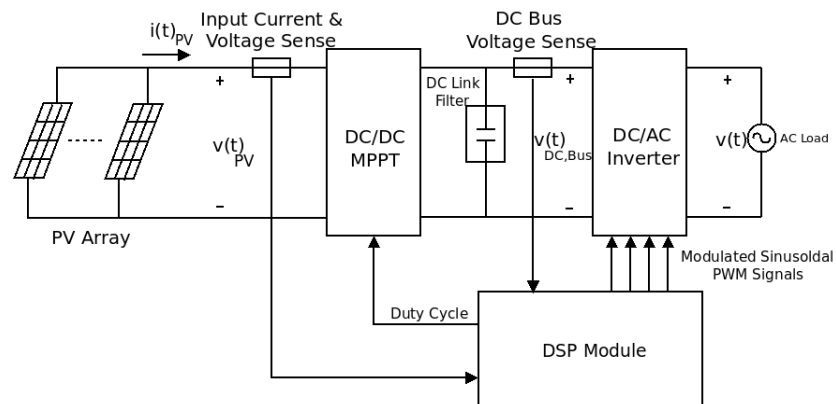
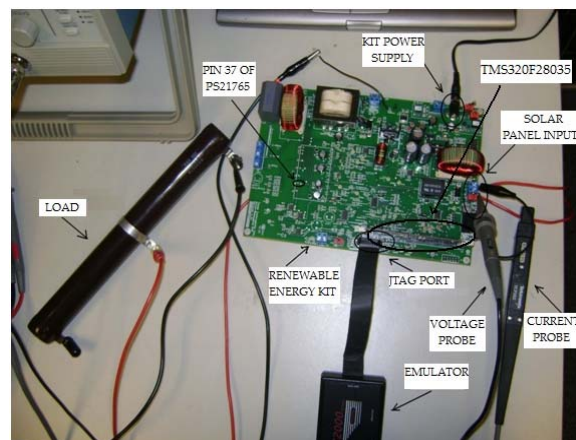


Figure 13: Photograph of the DSP Development Board and Connections to Other Parts of the System



2.12.3 Objectives

The goal of this project was to determine the feasibility of using a single fixed point digital signal processor to control the two converter stages needed for connecting a photovoltaic or fuel cell energy source to alternating current mains. The researchers incorporated additional features to achieve high efficiency and increased reliability. They established the following project objectives:

1. Demonstrate the feasibility of controlling the multiple stage power converters used in power conditioning of renewable energy systems by utilizing a single low cost, fixed point Digital Signal Processor controller.
2. Reduce the size of the energy storage bulk capacitor by using a modified pulse width modulation technique for inverter control thereby reducing the size 20 to 30 percent and improving reliability of the system.
3. Incorporate a new fast converging MPP tracking control method in the DC-DC converter stage to draw the maximum power from the PV source under all operating conditions with 97 percent efficiency.

2.12.4 Outcomes

The researchers achieved the following outcomes:

1. They used a single DSP controller (TMS320F28035 Piccolo Card by Texas Instruments) to control the two converter stages. They developed separate software modules for the DC-DC converter control and inverter control and tested integrated operation of the two modules. The cost of F28035, the fixed point Digital Signal Processor used in the implementation of this project, was \$6.76 which is 50 percent less than its floating point counterpart.
2. They reduced the DC link capacitor from 3600 microfarad to 47 microfarad and demonstrated that the proposed inverter control (implemented in the DSP controller) kept the inverter output voltage stable. Without the new inverter control system DC bus voltage ripple could be induced in the output voltage due to the use of the smaller capacitor. The reduction in size was about 98 percent, more than the 20–30 percent reduction targeted in the objective listed above. The cost of a 3600 microfarad capacitor was \$0.75, whereas the cost of a 47 microfarad capacitor used with the proposed algorithm was \$0.12, resulting in an 84 percent reduction in cost.
3. They used the DSP code implementing the proposed MPPT method to control the DC-DC converter. Experimental results showed that the PV panel operated at its maximum power point with a tracking efficiency higher than 92 percent for different insulations.

2.12.5 Conclusions

1. The researchers did a thorough job of demonstrating the efficacy of using a single DSP to control the two major pieces of the converter. However it is difficult to see why it matters whether one or two DSPs is used or whether integer or floating point is

incorporated. The cost of the electronics is dominated by design, software programming, high power switches, and other concerns. Present cost of such a system is typically more than \$1,000 (2,000 watts and \$0.5/watt), very much higher than the higher cost (\$6.76) of a floating point processor.

2. The researchers verified that the control algorithm was effective in correcting the AC power waveform to compensate for the input ripple caused by use of a small capacitor. Once again, the cost of the capacitor mentioned in the final report does not seem relevant, but the need for high reliability is easier to accomplish with a smaller value capacitor. A very reliable capacitor (a capacitor with a long mean time to failure) such as a motor start film dielectric type might cost \$10 in low quantity, but that price is acceptable if the overall life of the system is increased from two years to five years as a result of incorporating the more expensive component.
3. The researchers showed tracking the PV array to maintain peak power, called MPPT, worked, but the measured efficiency was 92 percent, a significantly lower result than the goal of 97 percent. Other algorithms are used in present day systems and most claim efficiencies of 95 percent or greater. This is an area of robust development where major improvements occur every year. This proposal represents the situation in 2007 and is no longer current.

The overall conclusion is that the approach taken and the research results are in agreement with how the field was evolving in 2007.

2.12.6 Recommendations

Any new proposal should address the technology changes that have occurred since the time when the project proposal was written. In addition, the researchers should distinguish their work from that of Texas Instruments, a company selling an inverter module that includes MPPT software.

Future work should make use of more modern technology, such as field programmable gate arrays (FPGA) that incorporate DSP functions along with many other features. Problems addressed should include a wide range of new developments such as safety features to enable connecting to the grid and the ability to operate in the master/slave mode for managing multiple arrays DC-DC converters.

2.12.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research would be reduced environmental impacts of the California electricity supply, transmission, and distribution system.

Reduction of emissions occurs because the use of renewable energy sources replaces generators burning carbon based fuels. In the future the evolution of smart inverters and the smart grid could also lead to major impacts on transmission and distribution.

Grid tied inverters were considered unreliable when they were first commercially introduced in the early 1980s. The proposed technology increases the reliability of the system, since DSP based control is inherently faster and more reliable due to the use of a smaller DC link capacitor. Capacitors are known for significantly reducing reliability of any system. With the proposed DSP based control, the size of the DC link capacitor at the inverter input can be reduced, resulting in a more reliable system. The project outcomes demonstrate that an 84 percent reduction in capacitor cost can be achieved by reducing the size of that component.

2.12.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.12.8.1 Marketing/Connection to the Market

The researchers have not completed a market assessment. They have written and submitted a technical paper to IEEE.

2.12.8.2 Engineering/Technical

The researchers estimate that another two to three years of development are required. They plan to write engineering requirements specifications to guide development in 2011.

2.12.8.3 Legal/Contractual

The researchers have received one patent and have applied for another. They plan to conduct a more thorough intellectual property assessment.

2.12.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

The researchers understand the need for safety features related to connecting to the grid. Environmental, risk assessment, and quality plans will be addressed as the technology approaches commercialization.

2.12.8.5 Production Readiness/Commercialization

The technology was not sufficiently developed at the completion of this project to have a commercialization plan.

2.13 Aquatic Biomass to Fuel

Awardee: Michael Cohen

Principal Investigator: Michael Cohen

2.13.1 Abstract

California has a large and diverse agricultural sector that naturally produces vast quantities of residual material that has potential recoverable energy content. California also has a large population that produces significant wastewater that requires treatment and residue that has recoverable energy content. Historically, much of this residue has not been utilized because energy conversion technologies have focused on individual residue types like dairy manure or vegetative crop residues or wastewater treatment, thus limiting economic and flexible energy recovery.

Vertical plug flow anaerobic digestion (VPF-AD) promises efficient processing of mixed feedstocks having high buoyancy components. For this project the researchers sought to refine and optimize VPF-AD bioreactor design and apply it to co-digestion of aquatic vegetation combined with agricultural by-products from wine and dairy operations. A twin bioreactor design allowed side by side comparison of operational conditions and performance. For the main experimental period, feedstock (2.6 percent to 3.0 percent dry weight with a carbon to nitrogen ratio of 11.3/1) was provided to both bioreactors maintained at $95 \pm 1^\circ \text{F}$ with a hydraulic retention time of 66 days. The reactors produced biogas composed of 61 percent methane (vol/vol) at rate of 222 to 336 liters methane per kilogram of volatile solids fed. When the researchers added a modified feedstock mix containing crude glycerin (a residual from biodiesel manufacture) in place of manure to one of the bioreactors, methane concentration of the biogas increased to 65 percent and the production rate rose to 792 liters methane per kilogram of volatile feed materials.

By enabling the co-digestion of diverse feedstock mixtures VPF-AD can improve the flexibility and cost effectiveness of anaerobic digestion, leading to expanded use and significant public benefit.

Keywords: Anaerobic digestion, vertical plug flow, co-digestion, biogas, methane, cow manure, wine lees, aquatic vegetation, crude glycerin, biodiesel glycerol, bioenergy, *Thlaspi*

2.13.2 Introduction

California has a large and diverse agricultural sector that naturally produces vast quantities of residual material that has potential recoverable energy content. California also has a large population that produces significant wastewater that requires treatment and that has residue with recoverable energy content. Historically much of this residue has not been utilized because

energy conversion technologies have focused on individual residue types like dairy manure or vegetative crop residues or wastewater treatment, thus limiting recovery's economic potential and flexibility.

A more fully integrated approach could take advantage of multiple residue types, adding flexibility and improving economics and sustainability. This approach has been hampered by the inability of anaerobic digesters (AD) to handle feedstocks with different physical properties such as buoyancy.

In this project researchers demonstrated improved anaerobic digestion as part of an integrated system at the City of Santa Rosa Laguna Treatment Plant. In cooperation with the city, the researchers created an integrated waste management, energy generation, and crop cultivation demonstration system. Specifically, treated municipal wastewater flowed through a constructed wetland that removed residual nutrients and pollutants from the water while harvesting the sun's energy by growing aquatic biomass. Biomass harvested from the wetland served as a substrate for AD bioreactors, with the resultant methane being combusted to help power the treatment plant operations. Lastly, the digested biomass from the anaerobic digesters was used to enhance the growth of strawberries, completing the nutrient cycle. Successful operation of the system required the anaerobic digesters to treat buoyant aquatic vegetation successfully. In this project researchers demonstrated the integration of vertical plug flow anaerobic digestion (VPF-AD) into the overall integrated system. Figure 14 illustrates the VPF-AD installed at the treatment plant.

Figure 14: The VPF-AD System



2.13.3 Objectives

The goal of this project was to determine the feasibility of digesting aquatic vegetation in a modified plug flow digester to provide methane for electricity generation and a source of

carbon dioxide at wastewater treatment facilities in an integrated and sustainable fashion. The researchers established the following objectives:

1. Complete system design and specifications.
2. Demonstrate that the anaerobic digester (AD) system mixing station is capable of regularly processing and delivering the necessary volume of feedstock to the bioreactors (~1 m³ within 15 day intervals) with operator safety.
3. Demonstrate that the bioreactors have a combined 8 m³ capacity for a 20 day retention time at an initial 0.4 m³ per day loading rate.
4. Demonstrate that the test stand is capable of measuring biogas production rate and percent CH₄ composition within an error of +/- 2 percent.
5. Demonstrate that the operational system can operate long term, at least 500 hours, without interruption and can produce a biogas that is greater than 60 percent CH₄. Also demonstrate that optimization of reactor operations leads to net energy production gains.
6. Confirm that the project benefits exceed lifecycle costs.

2.13.4 Outcomes

1. A professional engineering firm completed the project blueprints and specifications. Authorities granted permits by July 2009. Researchers completed construction of the system in November 2009.
2. The researchers demonstrated the feedstock mixing station was capable of continuously supplying the bioreactors with 0.14 m³ feedstock every other day (~1 m³ per 15 days). They corrected an initial problem with the installed plumbing, which had a tendency to clog.
3. The researchers achieved an operational culture volume of 8.5 m³ (4.26 m³, or 1125 gallons, per bioreactor) in late 2009. They maintained a stable methane producing mesophilic (95° F) microbial community. The researchers changed the retention time from the originally planned 20 days to 66 days to provide high conversion rates rather than high conversion yields.
4. The researchers used a gas analyzer to measure the produced gas at 61.2 ± 0.9 percent methane. They also measured, under experimental conditions, methane concentration of 65.2 ± 1.0 percent when crude glycerin was substituted for the manure component of the digester feedstock. They encountered initial problems with gas leakage of the bioreactors and corrected for errors in the readout of the gas flow meters by factors calculated based on direct gas flow measurements using water displacement tests.
5. The researchers compared the performance of the two bioreactors under differing conditions. They measured volume produced by the bioreactor mixed by circulating with the equivalent of one volume of culture at approximately 20 percent more biogas

per unit of feedstock than the one that was circulated with only ½ volume of culture. The researchers calculated that approximately 90 percent of the biogas generating potential was extracted from the feedstock. Methane from the bioreactors during this and a subsequent equilibration period was produced at rate of 222 L to 336 L per kg volatile solids. Substituting crude glycerin for manure resulted in production of 789 L methane per kilogram volatile solids.

6. The researchers compared the cost and the benefits of the system, acknowledging that some benefits of anaerobic digestion, such as methane generation and waste reduction, can easily be quantified while others, such as odor and pest control, cannot. They estimated that a single pilot project sized bioreactor could provide slightly less than \$1,000 per year in cost offsets and income.

2.13.5 Conclusions

The researchers demonstrated the feasibility of utilizing aquatic vegetation as feedstock for a modified plug flow digester to provide methane for electricity generation at wastewater treatment facilities in an integrated and sustainable fashion.

Vertical plug flow anaerobic digestion is a viable mechanism for digesting mixtures containing buoyant materials to produce methane and stabilized organic soil amendment. It can thereby serve to improve the economics of the use of aquatic vegetation in integrated water purification systems (e.g., constructed wetlands) as well as programs for removal of invasive water weeds. It could be integrated with biodiesel production by digesting crude glycerin from that process.

2.13.6 Recommendations

The researchers should develop a user guide useful for other wastewater and dairy manure treatment facilities contemplating installation of integrated systems using aquatic flora in constructed wetlands. This guide should include comparative economics of alternative treatment techniques. They should also reach out to developers of biodiesel facilities to cooperate on beneficial use of crude glycerin produced as residual material. Further, they should reach out to agencies that operate and maintain waterways that are plagued with invasive plant species to ensure those waterways are maintained in an environmentally sustainable fashion while controlling plant growth that impedes efficient flow. The researchers should demonstrate the effectiveness of the VPF-AD system using other aquatic and non-aquatic yet buoyant species as substrates.

Wastewater treatment facilities must often deal with trace level of heavy metals and pharmaceuticals in incoming waste streams. The researchers should characterize the fate of such contaminants after the wastewater is treated by the constructed wetlands. Various metal accumulators, such as *Thlaspi*, should be considered an additional component of a fully integrated system before the water is used on edible crops like strawberries.

The energy required for heating the feed mix and the bioreactors themselves constitutes approximately 84 percent of the total operational energy needs. Therefore net energy production could be greatly increased if the AD system were to be coupled to a solar heating unit. The feedstock mixing station overhang was south facing and would accommodate solar

panels. To more precisely monitor energy usage at the site, an electricity meter should be installed.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.13.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is from reduced environmental impacts of the California electricity supply system. Secondary benefits are associated with improved wastewater treatment facilities and waste disposal. The latter includes potential improved economics of biodiesel production by making beneficial reuse of crude glycerin from that process.

Overall, the methane produced and beneficially used could represent a reduction in greenhouse gas emissions of more than 3.2 million tons CO₂ equivalent otherwise produced from combustion of fossil fuel natural gas in the production of electricity.

A study conducted by Z. Zhang of the California Energy Commission found that of 3.9 million dry tons in recognized AD feedstocks available in California, only a small fraction (~11 percent) is actually processed by AD. This represents 232 MW in foregone energy generating capacity. Co-digestion could greatly boost methane production from the individual substrates that comprise the feedstock mix. Therefore expansion of co-digestion projects in California should be encouraged.

2.13.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.13.8.1 Marketing/Connection to the Market

The researchers have not yet published the results of this project and its applicability to other waste treatment applications, which will be necessary for the process to become widely accepted and applied. They plan to do so in scientific journals.

2.13.8.2 Engineering/Technical

The researchers do not have a precise plan to continue the technical work.

2.13.8.3 Legal/Contractual

The project did not develop new patentable technology. This may impede its ultimate success, as the economic benefits of commercialization may become diffuse.

2.13.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

The primary environmental risk associated with the technology is the transport of heavy metals and pharmaceuticals in the waste water to various media, especially edible food crops. Because it concentrates wastes that were formally more dispersed, combusted digester biogas can be regulated as a point source of nitrogen oxides even though it results in net lower NO_x release.

2.13.8.5 Production Readiness/Commercialization

The concept is ready for commercialization but initially in limited customized application. The concept requires individualized design, accounting for unique local conditions. However, design specifications could be made simple enough for any quality construction firm to build an operational system.

2.14 Wind Turbine Load Limiting Algorithm Verification Testing

Awardee: University of California Davis

Principal Investigator: C.P. "Case" van Dam

2.14.1 Abstract

Increasing the amount of renewable energy remains a high priority in California. The likely expiration of Production Tax Credit and Section 1603 grants will mean that renewable producers, including wind energy producers, need to become more cost competitive. One method to lower the cost of energy is to improve turbine lifetime and reliability by mitigating damaging loads caused by volatile and gusty winds. The blade pitch systems in modern commercial wind turbines react slowly to wind gusts, which can generate significant bending and twisting stress loads on the blades. These loads are repeated thousands of times over the

life of a turbine. On occasion the loads have resulted in blade or turbine failure. More frequently the increase in blade fatigue leads to shorter blade and turbine life.

Impacts from the short term occurrences of these high loads could be reduced if the pitch controller correctly anticipated these gusts and adjusted blade pitch before the gust occurred. This project examined the effectiveness of a turbine pitch control strategy called the Load Limiting Algorithm (LLA) to be implemented in conjunction with a conventional pitch controller.

The effectiveness of the LLA was tested through numerical analysis and field experiments. Researchers performed numerical studies on two different turbine configurations, the 600 kW Controls Advanced Research Turbine (CART) and the NREL 5 MW models. The primary metrics of LLA effectiveness are blade fatigue damage, measured in 20 year damage equivalent loads (DEL) for flap bending and annual energy production (AEP). Numerical results indicated a reduction in weighted flap bending DEL (Flap DEL) for both turbine platforms. The CART demonstrated a reduction of 3.5 percent with a half percent loss in AEP. The LLA was more effective on the NREL 5 MW, demonstrating a reduction of 5 to 9 percent in Flap DEL with a reduction of 1 to 3 percent in annual energy production. Field tests on the CART verified the LLA's impact on turbine operation.

Keywords: Wind turbine, fatigue damage, pitch control, energy production, field test, damage equivalent loads

2.14.2 Introduction

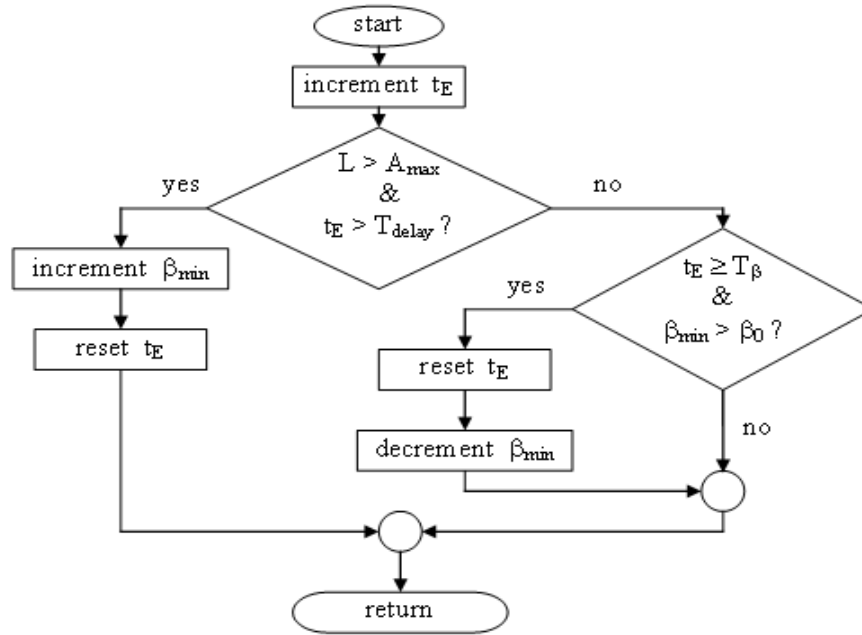
Increasing the amount of renewable energy remains a high priority policy in California. The likely expiration of Federal Production Tax Credit and Section 1603 grants will mean that renewable producers must become cost competitive.

One method to lower the cost of electricity for wind energy facilities is to improve wind turbine lifetime and reliability by reducing damaging loads caused by volatile and gusty winds. The blade pitch systems in modern commercial wind turbines react slowly relative to wind gusts. This can generate significant bending and twisting stress loads on the blades. Such loads are repeated thousands of times over the life of a turbine. On occasion these loads have resulted in blade or turbine failure. More frequently the increase in blade fatigue leads to shorter blade and turbine life.

One approach that could reduce load and fatigue is to have the turbine avoid high load situations. Impacts from the short term occurrences of high loads could be reduced if the pitch controller adjusted the blade pitch before the gust occurred. This project examined the effectiveness of a new pitch control strategy called the Load Limiting Algorithm (LLA) to be implemented in conjunction with a conventional pitch controller.

The innovation examined in this project avoids high load situations to lessen damaging loads while balancing the energy capture of the wind turbine. Figure 15 illustrates the logic of the load limiting algorithm.

Figure 15: Logic Diagram for the Load Limiting Algorithm



2.14.3 Objectives

The goal of this project was to verify that the Load Limiting Algorithm (LLA) was capable of limiting blade loads while limiting impacts on the energy output of the turbine.

The researchers established the following project objectives:

1. Produce and execute a CRADA³² that provides for sufficient testing and simulation to demonstrate the merits of the algorithm.
2. Produce a comprehensive test plan that will be capable of verifying the algorithm performance.
3. Demonstrate a 30—50 percent decrease in Rain Flow/Miner's Rule³³ annual fatigue damage of the blade roots over a standard IEC 61400 Class 2 wind spectrum while using the algorithm in comparison with the machine operating over the same wind spectrum without the algorithm.

32 Cooperative Research and Development Agreement (CRADA) is an agreement between a government agency and a private company to work together on research and development under the Federal Technology Transfer Act of 1986 (P.L. 99-502).

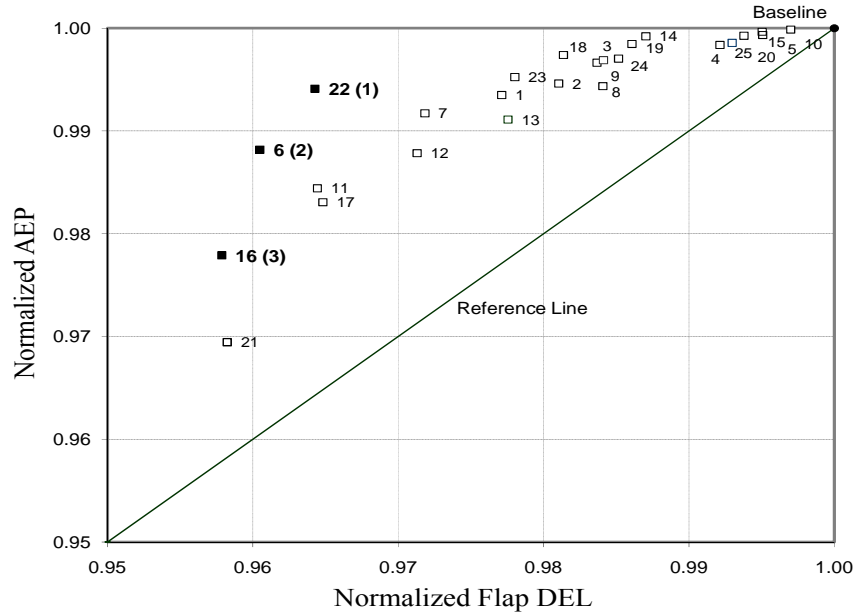
33 The rain flow counting algorithm is used in the analysis of fatigue data to reduce a spectrum of varying stress into a set of simple stress reversals. Its importance is that it allows the application of Miner's rule to assess the fatigue life of a structure subject to complex and cumulative loading.

4. Confirm the CART simulations by field testing the algorithm on the CART machine. When mean and TI of actual winds are within 5 percent of the simulated winds, the RMS of the blade root strain gages should be within 10 percent of simulated values. Some test winds should be greater than 30 m/s.
5. Demonstrate that the GEC 2.5 MW variable speed turbine model with a 15 percent larger diameter rotor has no higher annual fatigue damage over a standard IEC 61400 Class 2 wind spectrum than the same machine with a standard rotor without the algorithm.

2.14.4 Outcomes

1. After discussions with NREL and EISG, the researchers determined that a formal agreement in the form of a CRADA was not necessary to work with NREL staff and to test the LLA on the CART. NREL developed and operates the CART wind turbine specifically for testing wind turbine controls. This proved to be an appropriate platform to conduct LLA field tests. The researchers effectively achieved this objective.
2. The researchers developed a test plan that was reviewed by NREL staff, a professor at the University of the Pacific, and by the author of the LLA patent. The test plan included both the numerical analysis and field testing tasks and was periodically reviewed by NREL, UOP, and the LLA patent holder as testing progressed. The researchers successfully completed this objective.
3. The researchers calculated the reduction in fatigue damage measured in 20 year damage equivalent load (DEL) for blade root bending moment, Flap DEL, and annual energy production (AEP). The addition of energy capture as a metric limited the fatigue damage reduction provided by the LLA, as would be expected. The researchers used numerous turbulent wind profiles that corresponded to IEC 61400 Class 2 spectrums to compare the LLA performance with baseline performance. They successfully completed this objective. The researchers completed a numerical analysis to statistically compare the LLA against baseline operation. The two primary metrics used to measure the effectiveness of the pitch control strategy were AEP and weighted blade flap bending DEL (Flap DEL). The researchers successfully completed this objective.
4. The researchers field tested wind turbines controlled in baseline and with LLA control algorithms. They successfully completed this objective.
5. The researchers completed field testing of the LLA's impact on different turbine platforms. They selected the NREL 5 MW model to be used as the second platform instead of the GEC 2.5 MW. The NREL 5 MW model is a publicly available wind turbine model developed by NREL to be used by industry and academia as a benchmark. While the GEC 2.5 MW is commercially representative, it is a proprietary model that has prevented the authors from publishing all results. The researchers obtained 100 minutes of field test data. They partially completed this objective. Figure 16 shows data gathered.

Figure16: CART Results for 25 Numerical Tests



Results plotted as normalized AEP vs. normalized weighted blade flap bending DEL. The ranking value for the top three configurations is listed.

2.14.5 Conclusions

The Load Limiting Algorithm was shown to be a feasible addition to standard proportional integral derivative (PID) pitch controllers. The LLA incorporates a minimum pitch angle parameter, B_{min} , which is adjustable based on blade load measurements. The algorithm was designed to avoid high load situations caused by the combination of a reduced pitch angle and a sudden positive wind gust. Results from the CART numerical simulations showed a decrease in weighted Flap DEL of 3.5 percent and a marginal drop in AEP (0.5 percent). At mean wind speeds of 13 to 7 m/s, the LLA reduced Flap DEL by 5 to 8 percent. Secondary benefits of the LLA included reductions of 2 to 3 percent for weighted DEL for different load categories. The study for the NREL 5 MW model demonstrated an improved effectiveness for the LLA. Results indicated a reduction of 5 to 9 percent in Flap DEL with a corresponding drop in AEP of 1 to 3 percent.

If improved versions of the LLA are able to reduce loads with no significant impact on energy capture, existing wind turbine manufacturers and plant operators would be interested in adopting this technology. If implemented on new turbines, designers could rely on the LLA to minimize extreme and fatigue loading on the blades, thus decreasing the cost of energy. The simplicity of this algorithm and the potential benefits of its implementation suggest that there are many control strategy opportunities to improve turbine operation. Advancements in controls and sensors will play a critical role in the further advancement of the wind industry. Of course to be commercially viable, more sophisticated turbine controllers must be reliable, robust, and low cost to implement. The LLA's simplicity and its inclusion in commercially acceptable PID pitch controllers suggest that the LLA can be considered reliable, robust, and

relatively easy and low cost to implement in existing and new turbine controllers. The Load Limiting Algorithm could have a significant impact on wind turbine fleets around the world.

Since baseline and LLA data were captured in alternating fashion, the datasets had to be reorganized to create strings of baseline data and LLA data. Once this was completed, the researchers applied filters to remove unwanted situations. These included periods of high wind cutout (when the blades pitch to feather due to extreme winds) and when certain channels appeared to be working incorrectly. After the filtering was completed, the amount of usable data was reduced to about 100 minutes. Due to the limited amount of usable data, a statistical comparison of the blade loads was not possible.

The researchers did not conduct analysis of the effectiveness of the LLA on wind speed drop off and resulting rebound stress fatigue on the turbine blades.

The researchers successfully demonstrated the feasibility and application of the LLA.

2.14.6 Recommendations

The researchers should perform a life cycle analysis to determine the economic and financial tradeoffs from reduced fatigue and longer life versus reduced energy output. They should also investigate the practicality of using the LLA only during certain periods (for example, of low energy prices) while disabling the LLA during other periods (high energy prices). The researchers should determine the applicability of the use of the LLA on turbines of different composition, such as metallic versus composite blades. They should evaluate the impacts of using the LLA on rebound stress due to rapid drop off in wind as bending moments are relieved. The researchers should also gather data for longer and representative periods of weeks to months to confirm the early results based on 100 minutes.

There are a number of avenues to evaluate that could improve the LLA. These could include using different controller input sensors such as nacelle accelerometers or wind speed measurement devices or redesigning the control strategy to allow the minimum pitch angle parameter to adjust continuously rather than relying on time delays. The goal of these improvements would be to maintain the current level of load reduction but minimize the negative impact on energy capture.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.14.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. The primary purpose of the LLA is to reduce damaging loads on the turbine caused by turbulent winds. The LLA was capable of reducing the weighted DEL by 5 to 9 percent on the commercially representative 5 MW turbine model. Assuming that future versions of the LLA actually are used to reduce fatigue damage of turbine components and do not negatively impact energy performance of the turbine, the researchers estimate the price of turbine blades and tower could be reduced by about 10 percent, the overall turbine cost by 3.5 percent, and the installed cost by 2.6 percent. This would lower the cost of energy by 2 percent. A 20 percent reduction in blades and tower prices would decrease wind energy's cost of electricity by 4 percent. No estimate of lifetime extension is possible without longer test data collection.

2.14.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.14.8.1 *Marketing/Connection to the Market*

The results from the proof-of-concept studies presented in this paper demonstrate that the LLA has potential to reduce blade loads and other critical loads with little energy penalty. The researchers stated that private investors have expressed interest in the technology, but they have not surveyed potential customers.

2.14.8.2 *Engineering/Technical*

While the researchers proved feasibility of their concept, they plan some additional development work. They are seeking additional funding for that work.

2.14.8.3 *Legal/Contractual*

The technology is the subject of a patent held by Mr. Jerry McNearny. The researchers are working with Mr. McNearny to further develop and commercialize the technology.

2.14.8.4 *Environmental, Safety, Risk Assessments/ Quality Plans*

There are no known or anticipated environmental or safety risks associated with the technology.

2.14.8.5 *Production Readiness/Commercialization*

The product is ready for commercial demonstration, but not yet ready for widespread application.

2.15 Low Cost Hydrogen Sulfide Reduction in Biogas Energy Systems

Awardee: BioEnergy Solutions, LLC

Principal Investigator: Matthew D. Summers

2.15.1 Abstract

In this project researchers developed and tested an air injection system to remove hydrogen sulfide from biogas in two types of anaerobic digester systems. The project included the application of air injection technology to two types of digesters used in dairy biogas projects: covered lagoons and plug flow digesters. Air injection has previously been applied successfully to mixed bed digesters. Researchers in this study achieved the objective of reducing H₂S levels in the biogas to under ten parts per million by volume (ppmv) in two covered lagoons. In the plug flow digester that the researchers studied, the air injection system was not effective. At least for covered lagoons, a substantial reduction in treatment cost and increase in performance should improve the viability and deployment of these renewable energy systems.

Keywords: Anaerobic digestion, biogas, hydrogen sulfide, sulfur oxidation, gas scrubbing

2.15.2 Introduction

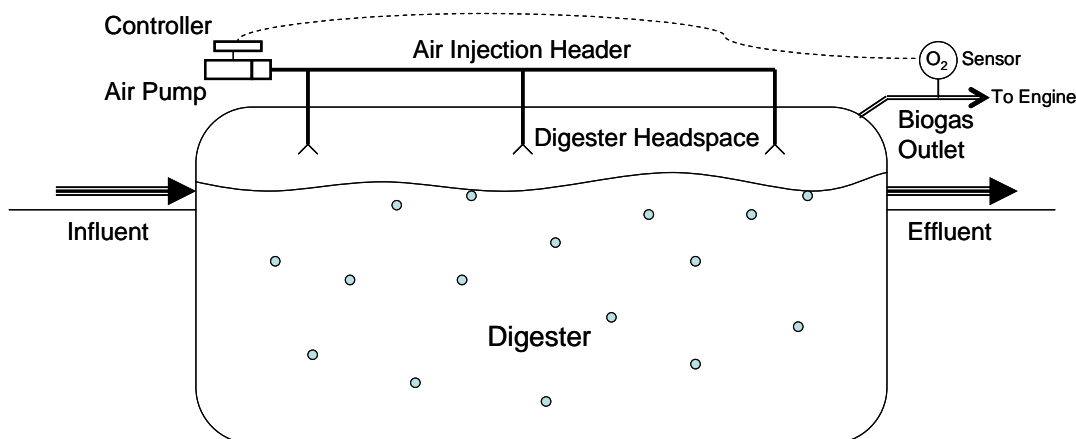
Conversion of biomass to energy is a high priority of California's energy policy. Conversion of biomass has the dual benefit of reducing fossil fuel use while reducing waste disposal and potentially reducing pathogen dispersal.

One of the most promising sources of energy conversion is anaerobic digestion of manure to produce methane (termed biogas in this conversion), an alternative to natural gas for use in reciprocating and other engines coupled to electric generators. One of the key technical issues with the use of anaerobic digestion systems is the hydrogen sulfide content in the biogas produced. Hydrogen sulfide adversely impacts systems like engines or boilers, poisons catalytic emissions controls systems, and prevents the gas from achieving pipeline quality standards. The economic impact of hydrogen sulfide is significant at digester facilities and restricts their wider application at facilities such as dairies and feedlots.

Current sulfur reduction technology has favored "iron sponge" type technology. This technology has a low capital cost relative to other desulfurization technologies but suffers from a higher operating cost and requires the disposal of the spent absorption material.

In this project researchers tested a simple system to oxidize reduced form sulfur compounds using an air injection system to remove the hydrogen sulfide formed in the anaerobic process. The researchers injected air into the collection headspace containing the product gas as illustrated in Figure 17.

Figure 17: Schematic Layout of Digester Air Injection System



2.15.3 Objectives

The goal of this project was to determine the feasibility of removing hydrogen sulfide from the product gas of biogas reactors in lagoon and plug flow configurations. The researchers established the following project objectives:

1. Develop designs for air injection systems for a covered lagoon digester and a plug flow digester.
2. Demonstrate the performance of the air injection systems in relation to the optimal air injection rate and system ability to maintain a constant air concentration in the biogas in the two digester types.
3. Demonstrate configurations of the air injection points that achieve an H₂S reduction in the biogas to below 10 ppmv.
4. Demonstrate the above air injection systems for at least 2500 hours of continuous operation.
5. Confirm that the projected installed cost would be no more than \$100/kW of generation capacity.
6. Confirm the parasitic load would be below 0.5 percent of the generation capacity and the projected operating cost would be below \$0.001/kWh produced.

2.15.4 Outcomes

1. The researchers developed three injection systems: one for a small covered lagoon digester with a single injection point, one for a plug flow digester with a single injection point, and one for a larger covered lagoon with six injection points.
2. The researchers measured the performance of the air injection system and measured hydrogen sulfide content at baseline (without air injection) and after extended runs in each of the digesters.
3. The researchers demonstrated that each air injection facility achieved the hydrogen sulfide removal performance shown in Table 3.

Table 3: Performance Level of Each of Three Injection Systems

Digester Facility	Giacomini Digester	Meadowbrook Digester	Gallo Cottonwood Digester
Type	Covered Lagoon	Plug Flow	Covered Lagoon
Biogas Generation Rate	17,000 SCFD	90,000 SCFD	400,000 SCFD
System Capacity	80 KW	175 KW	700 KW
Baseline H ₂ S Levels	1900 ppmv	3750 ppmv	2198 ppmv
No. of Air Injection Points	1	1	6
Air Injection Time to Reach 10ppm	4 hours	Never	31 hours
Minimum H ₂ S Levels Achieved	0 ppmv	3136 ppmv	0 ppmv

4. The researchers measured the hydrogen sulfide content of produced biogas after air injection had continued for longer than 2500 hours. They discontinued testing of the plug flow digester as hydrogen sulfide removal after 450 hours was negligible. Table 4 summarizes extended time performance, but it does not include injector start up or lagoon cover re-inflation periods.

Table 4: Performance Level of Two Covered Lagoon Systems after Extended Run

	Giacomini Digester	Gallo Cottonwood Digester
Total Operation Time (hours)	5088	2849

Baseline H ₂ S Concentration (ppmv)	1900	2198
<u>After Air Injection: All Readings</u>		
Mean H ₂ S Concentration (ppmv)	27	34
Mean H ₂ S Reduction (%)	98.6%	98.5%
<u>After Air Injection: Stable Operation Only*</u>		
Mean H ₂ S Concentration (ppmv)	4	9
Mean H ₂ S Reduction (%)	99.8%	99.6%

5. The researchers tabulated the projected installed costs for the two covered lagoon systems as shown in Table 5. They did not report capital cost for the plug flow digester.

Table 5: Installed Cost for Two Covered Lagoon Air Injection Systems

	Giacomini Digester	Gallo Cottonwood Digester
Installed Capacity (KW)	80	700
Total Installed Cost	\$ 20,650	\$ 35,350
Cost/KW	\$ 258	\$ 51

5. The researchers estimated the parasitic load and the projected operating cost for the systems developed in the study, as shown in Table 6. They did not report load or operating cost for the plug flow digester.

Table 6: Estimated Parasitic Load and Operating Costs for Two Covered Lagoon Systems

	Giacomini Digester	Gallo Cottonwood Digester
Installed Capacity (KW)	80	700
Air Injection Load (KW)	0.093	0.567
Total Parasitic Load	0.12%	0.08%
Total Operating Cost(\$/KWh)	\$0.0011	\$0.0003

2.15.5 Conclusions

The researchers demonstrated that air injection is a feasible approach for reducing hydrogen sulfide in covered lagoon style biogas digesters. Performance and capital and operating costs

met the project objectives for the covered lagoon systems. The researchers did not demonstrate feasibility for plug flow digesters.

2.15.6 Recommendations

The researchers should undertake a failure mode analysis to determine why the covered lagoon systems performed well while the plug flow system did not perform at all. This is important for both high solids (e.g., plug flow) digesters as well as for the lagoon style systems. Designers and installers of air injection systems need to understand the failure modes that may not be unique to high solid systems to avoid such failures in covered lagoons. Some of the possible reasons for the failure of the plug flow system that they should investigate include:

1. Head space mixing of digester gas before and after installation of the injection system including geometry that may lead to laminar flow rather than turbulent mixing and effective resident time.
2. Temperature of head space during injection and stoichiometric ratios of injection air versus sulfide content and versus methane and CO₂ content.³⁴
3. Trace contaminants that may have acted as retardants or conversely as accelerants in the successful covered lagoons. For example, biogas can also contain small quantities of water vapor, hydrogen sulfide (H₂S), ammonia (NH₃), hydrogen (H₂), nitrogen (N₂), and traces of lower fatty acids and alcohols. Ammonia or the lower fatty acids/alcohols may affect the core hydrogen sulfide reaction.
4. Time pattern of sulfide production after plug introduction versus biogas production.
5. Permeability of internal solids cover (scum layer) to product gas and to sulfides.

The researchers should evaluate and demonstrate their air injection system for covered lagoon digesters using non-dairy wastes such as swine and poultry which have higher nitrogen content than dairy, as well as food processing waste which has lower nitrogen content than dairy. After resolution of technical issues with plug flow digesters, the researchers should evaluate other types of waste.

Finally, the researchers should determine cost implications of requiring back-up hydrogen sulfide removal as protections for downstream engine/generator equipment during start up and set up conditions.

2.15.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

³⁴ The methane content of biogas can easily fluctuate between 45 percent and 70 percent, while CO₂ may fluctuate between 25 percent and 55 percent. Water vapor and ammonia have similarly wide ranges. While these ranges are the result of digester stability, they can dramatically affect reactions within the headspace and are especially serious in plug flow digesters.

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. Secondary benefits are reduced environmental impacts and waste disposal issues.

The permanent air injection systems installed during this study could reduce the need for sulfur adsorbent at California anaerobic digester facilities, resulting in an estimated annual operating cost savings of \$95,000 at typical dairy sited lagoon digesters.

If adopted widely on anaerobic digesters used to generate electricity, air injection technology would help reduce the cost of this renewable energy source in California. Operating costs could be reduced from \$0.01 to \$0.02 per kilowatt hour to less than \$0.001 per kilowatt hour.

Considering only future dairy digester installations in California, these systems could net an annual cost savings up to \$20 million and eliminate 35 million cubic feet of hydrogen sulfide (1500 tons sulfur) without need for sulfur adsorbent use and disposal.

Market studies must confirm the potential application of this technology to existing dairy facilities in California. Additional savings could be realized if this technology could be retrofitted to current digesters.

2.15.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.15.8.1 *Marketing/Connection to the Market*

The researchers claimed one major California digester developer expressed interest in using this system on all its future covered lagoon digesters. The researchers discussed the concept with other digester developers.

2.15.8.2 *Engineering/Technical*

The researchers stated that they could complete product development in one to two years.

2.15.8.3 *Legal/Contractual*

The researchers had not performed a patent search nor had they applied for a patent at the end of this project.

2.15.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

The researchers had not completed these plans at the end of this project. Environmental benefits must be confirmed by independent testing.

2.15.8.5 Production Readiness/Commercialization

The technology is not yet ready for deployment. The researchers had not produced a commercialization plan.

2.16 Charge Air Chiller

Awardee: Energy Concepts Company, LLC

Principal Investigator: Dr. G. Anand

2.16.1 Abstract

This project proposed the development of a three stage inlet charge air chiller concept, the Thermo Charger, to increase the efficiency of spark ignited turbocharged natural gas internal combustion (IC) engines. The greatest efficiency gains would occur at sites with high ambient temperature. A key innovation of the concept was that all stages would be powered by engine waste heat and would thus result in no parasitic power loss. Turbochargers can pressurize the inlet charge to about two atmospheres and raise its temperature to over 300° F. The first two cooling stages would cool the inlet charge to about 120° F, depending on the ambient temperature. The final absorption cooler stage would cool the charge to 45° F, nominally independent of ambient temperature. For a fixed mass of inlet charge, the lower temperature of the charge would reduce the compression work done by the engine and increase its efficiency. The researchers calculated that introducing chilling of the charge in the last stage charge chiller would increase engine power by about 9 percent. However, since it would have to be throttled back, it would increase throttling or pumping losses somewhat for a net efficiency gain of about 6 percent.

To test the concept, the researchers used an existing 300 kW spark ignited and turbocharged natural gas IC engine generator set. The engine contained a conventional ambient water cooled intercooler. In this project researchers designed and fabricated a final stage refrigerated inter-chiller of 10 ton capacity and installed it between the existing intercooler and intake manifold. Chilled water supplied to this inter-chiller cooled the charge to about 50° F. Tests, however, did not show any efficiency improvements. The researchers speculated that efficiency improvements were limited by the existing turbocharger which introduced throttling losses at the intake side and additional back pressure in the exhaust. They also speculated that a higher level of optimization of the engine control unit would be required to maximize efficiency by adjusting air/fuel ratio and spark timing and by controlling turbo boost pressure. Intake charge

air chilling did, however, enable the engine to operate at 9.1 percent higher peak power. Higher gains were limited by lube oil and generator set cooling. If these cooling demands were addressed with additional waste heat powered absorption chilling, the researchers projected gains of 40 percent in power and 30 percent in efficiency. However this project did not address those additional cooling loads.

Keywords: Thermo Charger, engine, efficiency, waste heat, chilling, intercooler, absorption, ammonia water

2.16.2 Introduction

Distributed energy resource (DER) technologies promise high efficiencies, low emissions, increased flexibility and reliability, cost effectiveness, and environmentally sound alternatives to the traditional electric utility infrastructure. Distributed generation (DG) is a valuable and growing component of California's DER portfolio. DG application provides specific benefits to the end user which determines the target markets. In general, these include standby power generation, peak shaving, combined heat and power, and resource recovery. California has about 3.7 GW of installed grid tied DG.³⁵ These figures do not include emergency or other non-interconnected DG. For comparison, California's peak electrical demand is about 60 GW^{36,37} and its total in-state supply is about 61 GW.³ Since the national average cost for adding transmission and distribution infrastructure is high at about \$1,260/kW, the potential savings from DG are large.³⁸

Of the various DG power methods (fuel cell, turbines, reciprocating engines, etc.) reciprocating internal combustion (IC) engines have the lowest installed capital costs of \$300/kW to \$800/kW, depending on size.³⁹ Reciprocating engines are the most common and most technically mature of all DG technologies and are the most commonly used technology for distributed generation today.⁴⁰ They are available from small sizes (e.g., 5 kW for residential back up generation) to large generators (e.g., 7 MW), and they use commonly available fuels including natural gas and diesel.⁴¹ Natural gas is usually less expensive than diesel for the same heat content. If the IC engine is to be used for a large number of hours per year, the total cost to operate the gas unit may be lower than diesel. Diesel engines can, however, be more efficient than gas due to their

35 <http://www.energy.ca.gov/distgen/markets/markets.html>

36 http://www.energyalmanac.ca.gov/electricity/historic_peak_demand.html

37 <http://www.energy.ca.gov/2010publications/CEC-200-2010-003/CEC-200-2010-003.PDF>

38 <http://www.energy.ca.gov/distgen/markets/electricity.html>

39 <http://www.energy.ca.gov/distgen/economics/capital.html>

40 http://www.energy.ca.gov/distgen/equipment/reciprocating_engines/applications.html

41 http://www.energy.ca.gov/distgen/equipment/reciprocating_engines/reciprocating_engines.html

higher compression (expansion) ratios, but their emission levels are higher, and their use is significantly restricted in California.⁴² This project proposed to decrease the compression work of turbo charged gas engines and thus increase their net efficiency by 6 percent through chilling of the high inlet temperature charge to the engine. Higher peak power and lower emissions would also be achieved.

The benefits to California ratepayers through a 6 percent increase in efficiency would be significant. The reciprocating engine is the most commonly used technology for distributed generation today. To estimate the size of the potential impact, the researchers assumed a market penetration of 2.5 GW of the 3.7 GW of installed California grid tied DG and an average efficiency for IC engine DG of 35 percent.⁴³ Thus the annual energy consumption would be 6.26×10^{10} kW hr or 2.14×10^{14} Btu. A 6 percent efficiency improvement on this amount would correspond to an energy savings of 1.28×10^{13} Btu. Assuming a market penetration of 25 percent and a cost of natural gas of \$4.17/MBtu,⁴⁴ this would correspond to a statewide cost reduction to the ratepayer of $\$13.4 \times 10^6$.

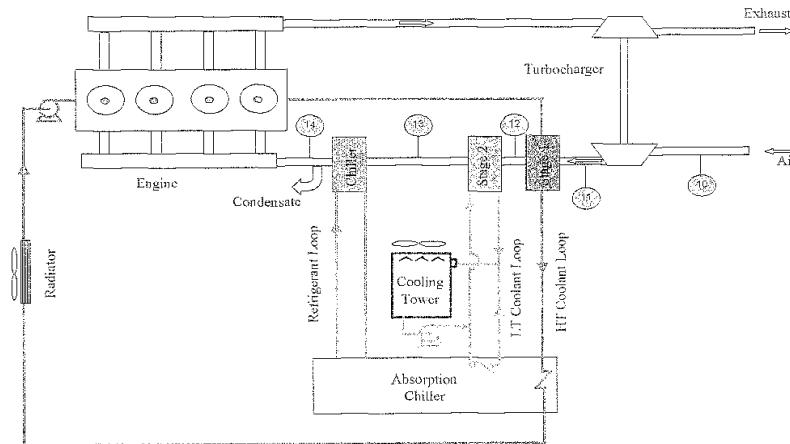
The advancement of science or technology that was proposed in this project was development of a three stage inlet charge air chiller for spark ignited turbocharged natural gas IC engines. A schematic of the engine and inlet chilling stages is shown in Figure 18. The key innovation was that all stages would be powered by engine waste heat and result in no parasitic power loss. Turbocharging pressurizes the inlet charge to about two atmospheres and raises its temperature to about 300° F. The first two cooling stages would cool the inlet charge to about 120° F, depending on the ambient temperature. The final ammonia water absorption cooler stage would cool the charge to 45° F, nominally independent of ambient temperature. Thus the greatest benefit would accrue at sites with high ambient temperature. The lower temperature inlet charge for a fixed mass of inlet charge would reduce the compression work of the engine. The researchers calculated that introducing chilling of the charge in the last stage charge chiller would increase the engine power by about 9 percent for a fixed fuel input. However since the engine would have to be throttled back, it would increase throttling or pumping losses, for a net efficiency gain of about 6 percent.

42 http://www.energy.ca.gov/distgen/equipment/reciprocating_engines/cost.html

43 Robert Zogg, Chad Smutzer, Kurt Roth, and James Brodrick, "Using Internal Combustion Engines For Distributed Generation", *ASHRAE Journal*, March 2007, p.76.

44 <http://www.eia.doe.gov/oog/info/ngw/ngupdate.asp>

Figure 18: Schematic of Engine with Three Stage Inlet Chiller



2.16.3 Objectives

The goal of this project was to determine the feasibility of increasing reciprocating engine fuel efficiency by using waste heat to chill turbocharger air to 45° F. The critical feasibility issues to be addressed were whether the additional amount of undercooling and chilling could be accomplished at reasonable size and cost of equipment and acceptably low pressure drop (e.g., less than 1 psid) and whether the existing Woodward Governor control system could adjust engine operating conditions sufficiently to take full advantage of the reduced charge temperature.

The researchers established the following project objectives:

1. Perform system design. Confirm design with 210° F to 230° F waste heat. Confirm cost below \$2000/refrigeration ton (\$600/kW).
2. Design charge air cooling coils. Demonstrate air pressure drop below 10" WC (water column) per coil.
3. Fabricate intercoolers. Demonstrate compact size.
4. Supply balance of system.
5. Install system.
6. Test and verify. Confirm 5 to 6 percent efficiency gain.

2.16.4 Outcomes

1. The researchers designed the charge air ammonia absorption chiller with operating conditions specified for 9.96 tons of chilling. This would chill the charge air from 105° F to 52.14° F. The absorption chiller was optimized with a COP (efficiency) of 0.708 with the desorber operating between 190° F to 244° F. The researchers estimated the installed unit cost of a 10 ton chiller to be below \$20000 or \$2000/ton at a level of production of 100 units per year.

2. The researchers designed the three stages of the charge air cooling using a helical coil design in two iterations. The calculated combined pressure drops for the two designs were 12.3" and 20.75" WC. In all cases the individual stage pressure drops were less than 10" WC per coil. The final stage was designed for using 35° F chilled water available at the test site (instead of an absorption cooler) capable of cooling the inlet to the 52° F design point for testing.
3. The compact fabricated chilled water intercooler was a 14" diameter vessel with chilling coil, condensate collection sump, and mist eliminator. It was placed after the existing test engine's intercooler.
4. The balance of the test system was an existing CHP installation at a vegetable processing facility in Blythe, California. It was based on a turbocharged lean burn Guascor gas engine and generator set. Significantly, the turbocharger did not have a waste gate. The engine operated at about 65 percent excess air. The engine control module adjusted the air fuel ratio. The researchers found that the engine maximum power had been previously de-rated to 275 kW at 26 percent efficiency from its 440 kW and 35 percent efficient design, evidently due to high ambient temperature conditions at Blythe. This was achieved by reducing the engine compression ratio from 11.8 to 10.
5. Researchers installed the fabricated chilled water loop between the existing water cooled intercooler and the engine manifold. Except for the interconnecting piping changes for the chilled water cooler, they made no other changes to the test engine or its controls.
6. The researchers performed efficiency measurements as a function of engine power output in both island mode and grid tied mode. The most straightforward to interpret results were in island mode. Researchers calculated efficiency by measuring the rate of gas consumption using the utility gas meter. They used a nominal lower heating value of 1000 Btu/ft³ to calculate the fuel energy input. They switched the chiller stage in and out of the intake manifold circuit, or in some cases they toggled its chilling effect on/off by turning off the chilled water flow. A significant result of chilling was that engine maximum power increased to 300 kW, a 9.1 percent increase. However no improvement in engine efficiency was apparent at any power level. The researchers stated that the engine could be run at 30 percent greater power, but its cooling systems were exceeded, setting off alarm circuits. By chilling not only the charge air but also the lube oil and generator and resetting the engine compression ratio from 11.8, the researchers proposed that the engine could be operated at much higher power and efficiency. The researchers did not provide calculations to show that sufficient cooling energy was available to cool the lube oil and the generator or that it was cost effective to do so.

2.16.5 Conclusions

1. The researchers achieved a successful design, meeting the design criteria. An estimate of cost per unit met the target cost. Therefore they met this objective.

2. The researchers designed three air cooling coils, and their calculated pressure drops achieved the design goals. Therefore they met this objective.
3. The researchers fabricated a compact chilled water intercooler for testing. It was not necessary to fabricate the first and second stages since the test engine already had them. Therefore this objective was substantially met.
4. The researchers supplied the balance of the test system. Therefore they met this objective.
5. The researchers installed the fabricated chilled water loop and instrumentation on the test system, meeting this objective.
6. Significantly, tests did not confirm an increase in efficiency due to chilling the intake charge. Therefore this most important objective was not met. The experimental data displayed no error bars.

In conclusion, the researchers did not prove feasibility of their central idea. They observed a 9.1 percent increase in maximum power with no increase in efficiency. They presented several speculations for the absence of efficiency gains. One was that fuel efficiency gains were limited by the existing turbocharger which introduced throttling losses on the intake side and additional back pressure on the exhaust side due to absence of a waste gate. They also suggested that to take full advantage of charge chilling a higher level of control optimization would be required to adjust appropriately air fuel ratio, boost control, spark timing, and intake valve timing.

2.16.6 Recommendations

The Program Administrator recommends that the test facility be given a greater degree of instrumentation to monitor important engine parameters. Gas flow and differential pressure sensors across different components of the intake and exhaust manifolds would allow throttling losses and back pressure losses to be monitored and measured. A waste gate would give an added degree of control over back pressure. In addition, a greater level of monitoring would also permit the researchers to follow changes due to the engine management control system. Finally, a method to measure fuel flow with greater precision and possibly accuracy is required. It appears that fuel flow was only measured to an accuracy of 3.0 percent at best, which was inadequate when the researchers were trying to see efficiency improvements of 5 to 6 percent. The Program Administrator recommends that error bars be assigned to all measured data to assess their significance. The researchers should include an engine manufacturer as a team member in any future work.

2.16.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system

- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. If the primary objective of a 6 percent increase in efficiency had been met, the benefits to California ratepayers would have been significant. Unfortunately, the researchers found no increase in efficiency from charge air cooling. They projected efficiency gains if cooling were applied to the charge air, plus lube oil and generator. However this project did not sufficiently develop the costs and benefits of cooling all three items.

2.16.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.16.8.1 *Marketing/Connection to the Market*

Energy Concepts plans to contact several engine manufacturers and partner with one that has the best potential to adjust its engine controls to maximize the chiller benefits.

2.16.8.2 *Engineering/Technical*

Energy Concepts plans to seek additional research funding to complete the engineering work. The future work will focus on engine tuning and controls.

2.16.8.3 *Legal/Contractual*

The researchers did not find any infringement with other patents. They reported that they had obtained a patent prior to the start of this project.

2.16.8.4 *Environmental, Safety, Risk Assessments/ Quality Plans*

These evaluations will occur during field demonstration of four prototype units.

2.16.8.5 *Production Readiness/Commercialization*

Energy Concepts has limited manufacturing capability to produce approximately one hundred units per year. The researchers will develop a commercialization plan after they demonstrate four units.

2.17 A New Approach to CO₂ Capture

Awardee: University of Wyoming

Principal Investigator: Maohong Fan

2.17.1 Abstract

Researchers in this project developed a new carbon dioxide sorbent based on K₂CO₃ and nanoporous FeOOH and investigated its performance to demonstrate improved carbon capture and sequestration (CCS). The new sorbent increased CO₂ capture capability by more than 70 times that of pure K₂CO₃. The sorption capacity of the KF sorbent reached its peak when its K₂CO₃ content was 33.33 percent by weight under the tested sorption conditions. The material's ability to capture CO₂ increased with an increase of moisture in gas and decreased with the elevation of temperature. The total CO₂ capture capability of the KF sorbent reached approximately 90 mg and 49 mg CO₂ per gram of sorbent at the sorption temperatures of 40°C and 60°C, respectively. CO₂ was desorbed at 125°C, a lower temperature than reported for other sorbents. Researchers estimated the energy demand of the CO₂ separation technology to be 1,500 kJ/kg of captured CO₂ under the condition that the multi-cycle CO₂ sorption capacity is approximately 30 mg CO₂/g sorbent. The sorbent is regenerable. Catalysis plays an important role in improving CO₂ desorption. The researchers estimated the energy cost for CO₂ capture at about \$19/ton CO₂, nearly twice the goal (\$10/ton CO₂) set for the project.

Keywords: Carbon dioxide capture, flue gas, potassium carbonate, FeOOH, adsorption, catalysis

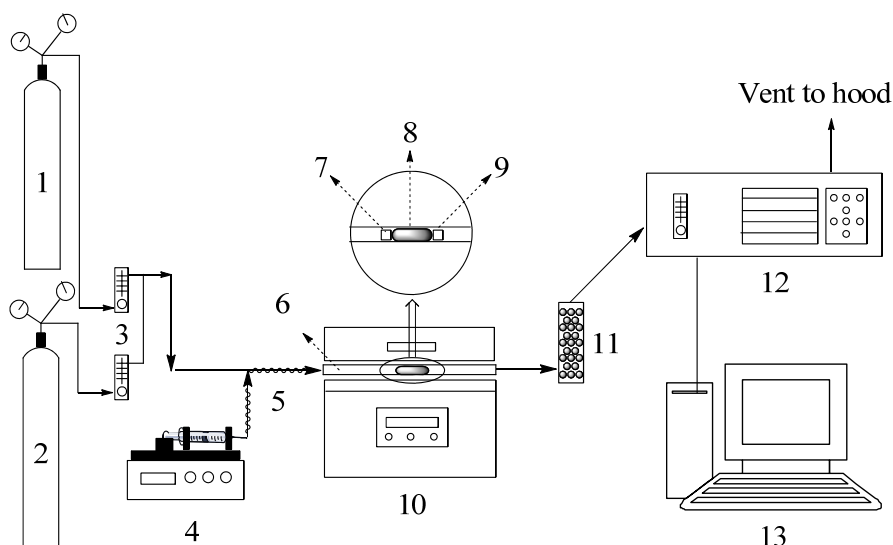
2.17.2 Introduction

Reducing greenhouse gas emissions, in particular CO₂, is the highest environmental priority in California. Efforts are underway to use less carbon based energy technology. However another way to reduce emissions is through carbon capture and storage (CCS.) Coal fired electric power plants have been the focus of CCS research, but the same technology is applicable to any facility fired by carbon based fuels or carbon based waste streams (e.g., cement kilns). While California has zero large coal fueled power plants, these technologies are equally applicable to natural gas fired power plants.

A variety of methods, including membrane separation, absorption with a solvent, and cryogenics, have been used to separate CO₂ from flue gases and other waste gas streams. Membrane technologies are promising for pre-combustion CO₂ separation such as in gasification since the pre-combustion gas stream contains a high concentration of CO₂ under high pressure, which is favorable to membranes. Post-combustion gases contain low concentrations of CO₂ and are under low pressures. Post-combustion CO₂ separation techniques are currently too expensive for commercial use.

In this project researchers formulated and tested a new sorbent for CO₂ capture from post-combustion flue gases. They formulated the new sorbent from potassium carbonate (K₂CO₃) and nanoporous ferric oxy-hydroxide (FeOOH). FeOOH is a common mineral used in removal of trace contaminants such as in potable water. The test setup is shown in Figure 19.

Figure 19: Schematic Diagram of Carbon Dioxide Separation Setup



1. carbon dioxide cylinder
2. nitrogen cylinder
3. flow meter
4. syringe pump
5. heat tape
6. quartz tube reactor
7. quartz wool

8. sorbent
9. quartz wool and notch block
10. tube furnace
11. water removal unit
12. multi-gas analyzer
13. data collection unit

2.17.3 Objectives

The goal of this project was to demonstrate the feasibility of using K₂CO₃/FeOOH as a regenerable nanoporous solid sorbent to reduce the energy required by 95 percent for post-combustion CO₂ separation in power plants. The researchers established the following objectives:

1. Demonstrate that the surface areas of the prepared sorbents are higher than 100 m²/g and that each gram of prepared solid sorbent contains at least 200 mg of K₂CO₃.
2. Demonstrate that the prepared sorbents can increase CO₂ sorption rates by at least 300 percent compared to their microporous counterparts and can achieve CO₂ sorption capacities of higher than 100 mg (captured CO₂/g solid sorbent).

3. Demonstrate that the prepared sorbents can increase CO₂ desorption rates by at least 300 percent compared to their microporous counterparts and are regenerable with their initial sorption capacity degradation being less than 5 percent after 50 cycles of sorption-desorption.
4. Demonstrate that the developed sorbents can reduce the energy consumption for CO₂ separation with an at least 95 percent efficiency to less than 1,000 kJ/kg CO₂ and the separation cost of CO₂ is lower than \$10/ton of captured CO₂.

2.17.4 Outcomes

1. The researchers prepared the KF sorbent by mixing FeOOH and K₂CO₃ solutions in water and then drying the mixture at 70° C to obtain a solid powder. The researchers then assessed the morphological characteristics of the supporting material (FeOOH) and the synthesized KF sorbent using a scanning electron microscope (SEM). They demonstrated that the KF sorbent synthesized in this research contained more than 100 mg of K₂CO₃. The surface area of FeOOH was measured at 181.6 m²/g.
2. The researchers conducted CO₂ sorption tests on pure FeOOH (supporting material) and the K₂CO₃ powder separately, as well as the KF sorbent, to measure the degree to which they adsorb CO₂. The researchers measured the total CO₂ capture capability of the KF sorbent which reached ~90 mg CO₂/g sorbent at the sorption temperature of 40° C. The CO₂ sorption capacity achieved with KF sorbent during the research was ~88 mg CO₂/g sorbent or ~277.7 mg CO₂/g K₂CO₃. The researchers demonstrated that the CO₂ sorption rate of nanoporous KF was more than 300 percent that of K₂CO₃ alone.
3. The researchers regenerated the KF sorbent at 125° C and measured its multi-cycle CO₂ sorption capacity to be approximately 94.1 mg CO₂/g K₂CO₃.
4. The researchers estimated the energy demand of the CO₂ separation technology at 1,500 kJ/kg of captured CO₂. The energy cost calculation was based on the assumption that the multi-cycle CO₂ sorption capacity is ~30 mg CO₂/g sorbent. The researchers estimated the energy cost of separation to be approximately \$19/ton CO₂, but they did not estimate the energy cost of regeneration or the overall cost.

2.17.5 Conclusions

The considerable decrease in decomposition temperature of KHCO₃ due to use of FeOOH in KF can decrease the energy cost of CO₂ separation with KF. Catalysis is important in improving CO₂ desorption, thus considerably reducing the energy required for CO₂ separation technology.

Temperature has a large effect on the sorbent CO₂ capacity. When the researchers conducted sorption tests at 40° C, CO₂ sorption capacity was as high as 90.0 mg CO₂/g sorbent. The CO₂ sorption capacity decreased to 49.2 mg CO₂/g sorbent when sorption temperature was 60° C. Moisture has positive effect on the CO₂ sorption capacity of KF. In general, the CO₂ sorption capacity of the KF increased with the increase of moisture in the tested moisture range of 7 to 8 percent by volume.

Flue gas in power plants fired by carbon based fuels contain higher levels of moisture and are typically higher in temperature than the moisture levels and temperatures used in this research. To assure performance at the higher moisture and temperature conditions, researchers should conduct evaluations at conditions typical of the proposed applications.

While the specific costs and performance objectives were not reached, in particular with respect to energy costs, the researchers achieved significant sorption capacity improvements compared to other sorbent approaches. Of particular importance was the demonstration of beneficial catalysis, which helps reduce energy costs for both sorption and desorption. The energy cost, even though it did not achieve the goal of \$10/ton CO₂, compared favorably with other measures (some adopted by CARB as mandatory) to reduce CO₂. The researchers did not prove technical feasibility since they failed to achieve stated performance objectives.

2.17.6 Recommendations

The researchers should complete a cost analysis beyond the energy costs of sorption and include regeneration costs and materials and engineering costs. They should compare costs to other control measures, not just CCS, for policy and regulations adopted by CARB include measures with costs in excess of \$20/ton CO₂.

The Program Administrator recommends that the researchers should:

- Measure the effectiveness, including regeneration, at various loadings of particulate matter (common in flue gas) and other pollutant concentrations (e.g., nitrous oxide) since they may affect the catalytic behavior and ability to regenerate the sorbent.
- Evaluate the sorbent's effectiveness at simulated flue gas conditions, including varying levels of CO₂ over ranges that could occur during ramping or cycling plants in response to varying loads and intermittent resources.
- Further investigate the impact of morphological properties of the sorbent and the extent to which those change with multiple regeneration cycles.
- Investigate other catalysts, either alone or in combination with FeOOH.
- Evaluate the use of the sorbent in non-coal fired power plants, such as natural gas fired power plants and cement kilns.
- Further improve performance of the sorbent and reduce costs towards the goals previously established.
- Estimate engineering and capital costs to calculate all costs for a complete CO₂ reduction module.
- Determine the acceptable variation in particle and pore size since that appears to have an effect on the sorbent's performance.
- Determine acceptable material variations to establish future production quality assurance standards.

2.17.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is from reduced environmental impacts of the California electricity supply, transmission, and distribution system.

Inexpensive CO₂ emission control technologies for power plants are needed for use in California. In 2010 the emissions from all power plants in California were 37.1 million metric tons.⁴⁵ By comparison, CARB staff estimated the total statewide 1990 emissions level at 427 MMTCO₂e, which sets the level of greenhouse gas emissions to be achieved by 2020.⁴⁶

The KF based CO₂ control technology could annually reduce the emission of CO₂ for California by approximately 35.25 MMT, assuming the 95 percent CO₂ separation efficiency is achieved when the technology is scaled up and finally commercialized. It could also annually reduce the emission of SO₂, NO_x, mercury (Hg), and fly ash for California by 1,197, 13.25, 0.27, and 428.7 tons, respectively, reflecting the reduced fuel consumption resulting from lower CO₂ capture energy requirements. The estimated reduction in SO₂, NO_x, Hg, and fly ash assumes continued import of coal based electricity from out of state, but controlled for CO₂ emissions. Emissions of all pollutants, in particular CO₂, could be further reduced if the sorbent is shown to work on other flue gases in natural gas fired power plants and cement kilns.

Furthermore, use of the KF sorbent for control of CO₂ emissions could save up to \$390 million annually for taxpayers, assuming the cost of the reference CO₂ separation technology is \$30/ton while that of the KF technology is \$19/ton. The cost saving could potentially be even more since CARB is imposing control programs with costs higher than \$30/ton.

2.17.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

45 California Air Resources Board, GHG Emissions Inventory, <http://www.arb.ca.gov/cc/inventory/inventory.htm>

46 *California 1990 Greenhouse Gas Emissions Level and 2020 Emissions Limit*, November 16, 2007, http://www.arb.ca.gov/cc/inventory/pubs/reports/staff_report_1990_level.pdf

2.17.8.1 Marketing/Connection to the Market

At this stage of development there is no connection to the market for CO₂ capture since the sorbent remains in laboratory development. The researchers plan to publish the results from this project, which should facilitate and spur others to pursue catalytic CO₂ sorbents. They have not yet identified any commercialization partners.

2.17.8.2 Engineering/Technical

The researchers estimate that it will take three to five years and approximately \$5 million in funding to complete product development and demonstration.

2.17.8.3 Legal/Contractual

The researchers have applied for patent protection, but have not yet been assigned a patent. They do not plan to publish results until a patent number has been assigned.

2.17.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

There are no known environmental or safety risks. There is a risk of degradation of the sorbent under actual flue gas conditions.

2.17.8.5 Production Readiness/Commercialization

The product is not ready for commercialization.

2.18 Demand Response Load Shedding System for Lighting

Awardee: Exergy Controls, LLC

Principal Investigator: Brian Rotty

2.18.1 Abstract

The researchers in this project addressed needed improvements in California's demand reduction programs through demonstration of an automated demand response technology for reducing peak lighting energy with minimal occupant disruption. This included building an interface to the emerging Open Automated Demand Response (OpenADR) communication standard and using it to control a typical lighting control system through two-way communication over the internet.

Testing at a school confirmed that a 27 percent demand reduction could be initiated automatically using an internet signal to the local lighting control system with results communicated back to the initiating server. A detailed specification for hardware and software

configurations, as well as the specific demand reduction steps for various targeted reductions, guided the work. The system's ability to gradually change lighting levels made its operation transparent to the occupants in this test.

Keywords: Lighting control, demand response, automated load shedding, electric peak reduction, digitally addressable, OpenADR, DALI

2.18.2 Introduction

California's electrical system must be planned to meet demand under all reasonably foreseeable conditions, including occasional peak days when demand is well above average. As a result a significant amount of costly generation, transmission, and distribution infrastructure lies unused for most of the year waiting to serve these relatively scarce spikes. The economics of such stand-by generation typically favor combustion turbines fueled by carbon based fuels, working against California's air quality goals.

Important strides have been made in reducing the magnitude of the peak demand, as well as overall electric consumption, through various demand and load management programs statewide. Introduction of smart meters and utility initiated demand management signals to customers calling for manual reductions during peak times are already providing benefits. However the effectiveness of these approaches is limited by several factors, including reliance on manual intervention by energy managers and an uncertain feedback to the utility confirming action has been taken. Customers may also resist or limit some demand management initiatives if they perceive a too drastic reduction in lighting levels or other comfort and convenience items.

A reliable system capable of transmitting utility demand reduction signals to customer premises, automatically initiating pre-determined local demand reductions, and notifying the utility of the result can increase the amount of demand management available, reducing reliance on standby electrical system infrastructure and improving air quality. Customer acceptance (and thereby penetration) of such systems can be enhanced by providing gradual transitions into and out of the demand reduced operating condition. There is continued interest in effective demand response systems in California prompted by their potential savings to customers and regulatory mandates for increasing amounts of demand reduction in utilities' resource plans. The ability to provide automatic implementation and two-way updates to the initiating utility should make the researchers' approach attractive.

With the potential benefits described in mind, the researchers in this project proposed utilizing an emerging communications standard, Open Automated Demand Response or OpenADR,⁴⁷ to develop and test a lighting control system (LCS) that would be addressable through the

⁴⁷ OpenADR was developed through pioneering work by the Demand Response Research Center funded in part by the PIER program. For details see <http://newscenter.lbl.gov/news-releases/2009/04/27/openadr-specification/>

internet. The system would automatically implement pre-determined demand reductions and notify the utility of their status, including lighting reductions, room occupancy sensor operation, and daylight harvesting systems, all with minimal occupant disruption.

2.18.3 Objectives

The goal of this project was to determine the feasibility of using a digital lighting control system in conjunction with local utilities to reduce peak electrical load levels with as little impact to room occupants as possible. The researchers established the following project objectives:

1. Establish design requirements for integrating demand response scenarios with lighting management systems. Prepare a document that addresses communication with utility, load shedding protocol, and control of advanced ballasts.
2. Develop demand response hardware and software. Based on a utility command, successfully reduce lighting energy consumption by 20 percent within five minutes of receiving the command to do so.
3. Integrate system in a laboratory mockup. Successfully demonstrate commissioning, load shedding, and daylight harvesting in a laboratory environment.
4. Install a full-scale demonstration system. Successfully reduce lighting energy use in a typical classroom environment by 20 percent based on a utility command. Demonstrate long-term, maintenance-free use of the system.

2.18.4 Outcomes

1. The researchers established design requirements through a survey of existing demand response products and interviews with key stakeholders and experts. This led to a comprehensive requirements document that included required actions for each element in a demand response system, data transmission formats based on the Open ADR demand response communication standard, a simplified example of a typical site, and savings targets for several levels of required demand response.
2. The researchers developed the hardware and software necessary to set up a benchtop system to test demand response handling. This included selection and programming of an OpenADR server/client interface and enhancing the hardware design of an existing LCS to allow two-way internet connectivity. After fabricating an upgraded circuit board for the LCS, the researchers successfully demonstrated receipt and sending of a demand response command to a targeted fluorescent ballast.
3. The researchers identified and implemented necessary hardware and software modifications to devices typically controlled by an LCS, including lighting fixtures/ballasts, motion sensors, photo sensors, and wall switches. Testing validated successful demand response in a laboratory scale system, including daylight harvesting, occupancy sensing, and pre-programmed wall switch settings at a targeted 20 percent energy savings.

4. A full scale installation and demonstration took place at a K-8 private school over a one month period. A basic LCS previously installed by the researchers' firm served as a starting point for the demonstration. The researchers installed an upgraded circuit board to provide LCS internet connectivity and new interface devices at the control devices from Objective 3 above. They then developed and installed protocols in the LCS for achieving the targeted 25 percent demand reduction through operation of daylight harvesting, wall switches, and occupancy sensors.

Test results showed successful two-way communications between the OpenADR server and the LCS/control devices, a 25 percent load reduction resulting from a 1/3 reduction in lighting footcandles and an ability to smoothly reduce loads over several minutes to minimize occupant awareness of the change.

2.18.5 Conclusions

The researchers proved the feasibility of using an OpenADR server/client communication system to transmit and confirm demand reduction instructions to an LCS equipped with an internet connection and compatible load control devices with smooth integration and operation. The field test suggested, but did not fully confirm, the hypothesis that achieving a 25 percent lighting load reduction is possible in widespread application with minimal occupant awareness through a slow and smooth transition period.

1. The requirements document provided high value from this research, setting forth a model for rigorous detail and stakeholder input prior to embarking on programming and implementation of a demand reduction protocol. Selection of the OpenADR standard took full advantage of ongoing PIER support of research at the Demand Response Research Center⁴⁸ and should help advance adoption of this standard in California.
2. The decision to have an upgraded LCS circuit board professionally fabricated for the project helped eliminate a possible failure mode if an add-on modification to the original circuit board were attempted.
3. The laboratory scale test provided useful insights into needed enhancements to both hardware and software to ensure the LCS and its controlled devices operated seamlessly across differing demand response implementation plans.
4. This research addressed two aspects of the demand reduction paradigm: a hardware/software system to implement lighting reductions and occupant behavior/acceptance of such reductions. The work performed on the former met its objectives well, although a longer duration field test would have better supported reliability in commercial application. However the limited duration test at a single site did not fully support the researchers' conclusion that well crafted and smoothly implemented lighting reduction protocols are likely to be imperceptible to occupants.

⁴⁸ See <http://drcc.lbl.gov/drcc-bg.html> for information about the center.

While that result was observed in this test, it is not clear whether this level of lighting reduction would yield similar results in other sites with differing lighting requirements.

2.18.6 Recommendations

This research demonstrated that internet enabled lighting control systems are feasible and offer benefits well beyond the simple manually operated systems prevalent today. The presence of competitors beginning to offer similar features indicates good commercialization potential. This potential can be enhanced through additional research, including:

1. Work with California's utilities to help ensure adoption of the OpenADR or other similarly effective communications protocols for their demand response applications. Consider repeating this research with other communications protocols.
2. Establish the likely user costs and benefits of typical commercial implementations of the researchers' design.
3. Survey and synthesize existing research into occupant receptiveness to varying levels of lighting reduction and consider longer duration field tests at larger facilities to better understand potential savings and impacts.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.18.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California electricity supply, transmission, and distribution system. Currently demand reduction activities depend on manual implementation actions by building engineers or occupants, with potential time lag, incomplete compliance, and difficult confirmation issues. An automated two way system would make a significant improvement in all of these and offer increased benefits from demand reduction programs.

A 5 percent reduction in peak loads throughout the nation is expected to save \$39 billion over 20 years. California is estimated to save roughly 8 percent of that amount (based on http://www.eia.doe.gov/emeu/states/_seds.html data) over the course of 20 years, totaling close to four billion dollars.

2.18.7.1 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.18.7.2 Marketing/Connection to the Market

Several vendors, including Tendril, Residential Control Systems, BuLogics, and Our Home Spaces, have adopted OpenADR for use in automated demand response products. Utilities serving northeastern California and Sacramento have identified OpenADR as their chosen communication protocol, and Honeywell is working with Southern California Edison to test the protocol. California's investor owned utilities currently use it to control over 70 megawatts of demand response.⁴⁹ OpenADR has also been selected by the National Institute of Standards and Technology and the U.S. DOE for smart grid demand response communications over the internet.⁵⁰

2.18.7.3 Engineering/Technical

The researchers estimated that product development would be completed in six months.

2.18.7.4 Legal/Contractual

The researchers had not conducted a patent search nor applied for any patents.

2.18.7.5 Environmental, Safety, Risk Assessments/ Quality Plans

The researchers suggested that a longer duration test be conducted as a logical next step. They planned expansion of such a test to include a broader diversity of test sites.

2.18.7.6 Production Readiness/Commercialization

The researchers' firm supplies manual lighting control systems. This capability shortens the lead time to modify equipment to include the hardware and programming involved in the tested system. There is substantial competition in automated demand response systems, including Honeywell's acquisition of Akuacom, and time to market will be critical.

49 See <http://greentechmedia.com/articles/read/honeywells-openadr-plans-for-socal-edison/>

50 See <http://automatedbuildings.com/releases/may10/100529110505openadr.htm>

2.19 Tandem Organic Solar Cell Using CNT and Mixed Quantum Dots

Awardee: UC Davis

Principal Investigators: Ning Pan

2.19.1 Abstract

The purpose of this work was to develop a tandem organic solar cell using carbon nanotubes (CNT) and mixed quantum dots, aiming to achieve high efficiency with low price. To acquire such an organic solar cell with enhanced power conversion efficiency, the researchers used several complementary approaches. First they adopted a low cost and environmentally benign process to synthesize quantum dots (CdS, PbS) *in situ* growing onto multi-wall carbon nanotubes (MWCNT). They then embedded the prepared MWCNT/CdS and MWCNT/PbS composites in the host polymer to form a tandem structure. The tandem structure covers a wider range of solar spectra to make fuller use of the solar energy. The researchers also proposed to develop new transparent conductive electrodes to replace currently used indium tin oxide (ITO) electrodes that are very expensive because of the rarity of indium. In addition, they studied graphene, a novel carbon material, for use as the solar cell counter electrode material to replace the expensive platinum electrode to reduce further the cost of solar cells.

Keywords: Quantum dots, MWCNT, tandem organic solar cell, graphene

2.19.2 Introduction

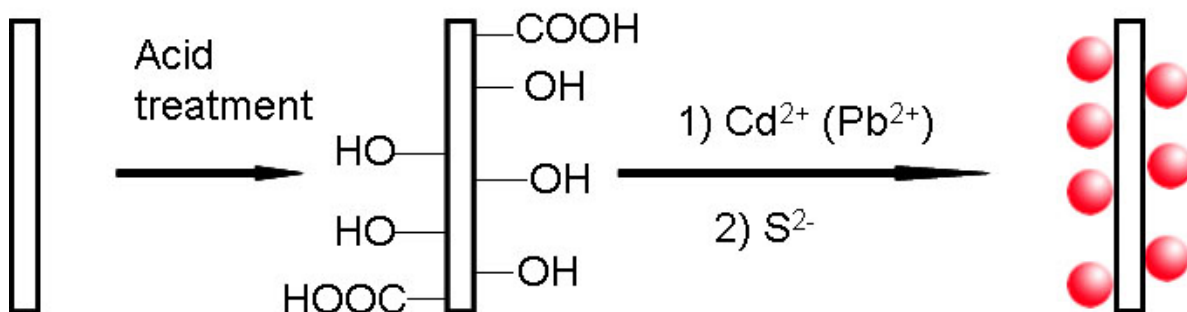
California has existing policies to expand the use of solar generated electricity, such as the “million solar roofs” program. The successful achievement of this policy has been hindered by the relatively high costs of solar to electric technologies.

Currently the majority of solar cells are made of inorganic semiconductors such as doped silicon (dSi) or gallium arsenide (GaAs). Although they possess relatively high power conversion efficiencies, such cells require many energy intensive processing steps including high temperatures and high vacuum conditions in manufacturing. This raises costs significantly and prevents wider acceptance and application. For example, a single crystal solar cell has efficiency over 20 percent, but its high cost has so far limited application on a large scale.

Organic solar cells are promising alternatives that use low cost materials, mainly conjugated polymers, yet still possess the same theoretical efficiency as conventional semiconductor devices. They combine both the optoelectronic properties of semiconductors and the mechanical and manufacturing properties of polymeric materials. That is, they can be fabricated easily at low cost by employing well established printing techniques in roll-to-roll processes. Organic solar cells have the potential of achieving economical viability for widespread power generation. However organic solar cells to date have low efficiency compared with that of silicon based solar cells.

In this project researchers developed a tandem solar cell using quantum dots and mixed carbon nanotubes (CNT) to improve the efficiency and lower the cost of organic solar cells. Figure 20 illustrates the scheme to deposit CNT and quantum dots on a substrate.

Figure 20: Scheme to Prepare MWCNTs/PbS QDs and MWCNT/CdS QDs Composites



2.19.3 Objectives

In this project the main goal was to develop a tandem solar cell with improved efficiency and lower cost using carbon nanotube and mixed quantum dots. The researchers established the following objectives:

1. Demonstrate CdS, PbS quantum dots and that PbS/MWCNT CdS/MWCNT composites can be synthesized using a simple and low cost method.
2. Develop a MWCNT film that can be used as a transparent conductive electrode.
3. Verify organic solar cells with low cost and high efficiency can be fabricated via tandem organic solar cells using MWCNT and mixed quantum dots.
4. Verify that the power efficiency of the tandem cells is greatly improved through the proposed strategies.
5. Verify the decrease of efficiency is smaller than 15 percent within 1000 hours and 35 percent within 2000 hours.

2.19.4 Outcomes

1. To demonstrate that quantum dots were successfully prepared, a researcher should provide direct proof using images from transition electron microscopy (TEM). However, the researchers in this project used the convenient and cheap UV-vis test to judge if the quantum dots were successfully prepared. They compared the absorption evident in experimental curves with known curves in references. The researchers suggested that some successful TEM pictures would have been desirable. They claimed that because their UV-vis spectra were “similar to those of previous reports,” the dots were successfully prepared. They did not include any examples of those previous results (only references to the work), making direct comparison more difficult. More

importantly, they did not make an effort to indicate what aspects of the spectra were actually indicative of success or how failure modes would differ.

2. The researchers reported the transparency was “about 82 percent” and the resistance was “about 212 k Ω /SQ” The transparency met the goal, but the resistance was higher than that of ITO (less than 100 k Ω /SQ).
3. The researchers “thought” the new technology was cheaper and better than that of silicon.
4. The researchers did not complete this objective.
5. The researchers did not complete this objective.

2.19.5 Conclusions

Most of the evidence suggested the researchers successfully prepared CdS, PbS quantum dots and PbS/MWCNT (CdS/MWCNT) composites via a simple and low cost method. They also fabricated transparent conducting MWCNT films via the drop casting method. The transparency of the films prepared in this project can satisfy the requirements for solar cells, but their conductivity is lower than commercial technology with the same transparency. Thus the related parameters in fabricating the MWCNT film must be improved to achieve better performance. The researchers demonstrated that tandem solar cells using carbon nanotube and mixed quantum dots are potentially feasible. Significant work remains necessary to prove feasibility. Because the researchers did not complete Objectives 4 and 5, we know little about the efficiency and durability of the tandem cells prepared in this manner.

2.19.6 Recommendations

For future work the researchers should:

1. Assemble and test the performance of actual tandem cells using the deposition techniques evaluated in this project.
2. Investigate techniques to improve the efficiency through approaches such as expanding the spectral coverage and decreasing the series electric resistance.
3. Investigate whether graphene is a viable alternative to carbon nanotube sheets.
4. Investigate the various parameters such as diameters of MWCNTs used, assembly technique, and thickness of films to begin development of manufacturing protocols and quality needs.
5. Investigate other conductive transparent electrode materials, such as ZnO or fluorine doped SnO₂.
6. Assess and quantify the trade-off of reduced cost versus reduced efficiency and calculate the net benefits of their process.
7. Conduct a market assessment for the developed technology.

The researchers should engage a patent attorney and file for patent protection of the concept evaluated in this project. After more fully developing the technology, they should determine whether to file for process patents. After obtaining patent protection, the researchers should publish the results of their work on developing this new concept.

2.19.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of the California electricity supply system.

Solar derived electric energy is an attractive renewable energy source to reduce the emission of greenhouse gasses and air pollutants. Although silicon solar cells have high power conversion efficiency, their cost has limited widespread application. At the time of this project, the cost of silicon based solar cells was \$2 to \$4 per watt, while the cost of organic solar cells was estimated to be in the range \$0.1 to \$0.5 per watt. Organic cells usually operate at lower conversion efficiency. If the technology evaluated in this project were successful and used widely, electricity produced by solar energy could be closer in price to that produced by conventional technologies. For example, the University of California at Irvine estimated the costs of the million solar roofs program at about \$20 billion.⁵¹ This cost could be reduced by 75 to 90 percent if the solar cells described in this project were successful at \$0.3 per watt, or a savings to California of \$15 to \$18 billion. A utility size combined cycle gas turbine power plant cost about \$0.7 per watt in the same time period.

2.19.7.1 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

51 <http://www.physics.uci.edu/~silverma/actions/MillionSolarRoof.ppt#256,1>. "An Analysis of California's Million Solar Roof Initiative."

2.19.7.2 Marketing/Connection to the Market

The researchers discussed their technology concept with venture capital firm, including Precision Technology of Olympia, Washington, but had not otherwise performed a market analysis.

2.19.7.3 Engineering/Technical

The researchers projected the need for another \$100,000 and 1.5 years to complete the development and definitely prove feasibility. They had not developed a path to product demonstration.

2.19.7.4 Legal/Contractual

The researchers undertook a self-directed search for conflicting patents and found none. They had not filed for patent protection by the end of this project.

2.19.7.5 Environmental, Safety, Risk Assessments/ Quality Plans

The researchers had not begun the evaluation of environmental or safety risks in the manufacturing steps associated with Pb and Cd as quantum dots. Quality plans are premature until the technology is proven feasible.

2.19.7.6 Production Readiness/Commercialization

The technology is not ready for production or commercialization until the above technical and market issues are resolved.

2.20 High G-load Combustor for Microturbines

Awardee: The Pennsylvania State University

Principal Investigators: Domenic A. Santavicca

2.20.1 Abstract

Landfill gas (LFG) is a significant sustainable energy resource in California. Its combustion in microturbines is an attractive option for distributed electrical generation. However, the California Air Resources Board has set stringent limits for 2013 on the allowable levels of NO_x production in combustion. NO_x production is a thermally activated process that is reduced by lower combustion temperatures. The combustion temperature in microturbines can be lowered by premixing fuel and air and adjusting the fuel air ratio (equivalence ratio) to the extreme lean limit. However, there is a limit to the degree of leanness set by the lean blowout (LBO) limit at which the flame is lost.

This project investigated the feasibility of an advanced microturbine combustor concept (g load) combustion with trapped vortex chamber) to extend the lean blowout (LBO) limit and hence to further decrease NO_x emission. The researchers fabricated a test rig based on an Ingersoll Rand microturbine combustor, which they modified to include a trapped vortex chamber (TVC). They investigated the effect of a wide range of g load (770 to 5050 g) on the flame regime. The flame stabilized in the TVC when the equivalence ratio was near the LBO limits. The novel combustor design concept extended the lean blowout limit to marginally lower levels. Significantly, the LBO limit was found to be dependent on the increase in residence time rather than g load. This indicated the increase of turbulent velocity with respect to g load was not the reason for the extension of LBO limits. This new combustor concept could enable microturbine operation at lower equivalence ratios, reducing the NO_x emissions as much as 30 percent. The data produced in this study could be used by Ingersoll Rand to optimize this concept to develop and to qualify a combustion system to achieve the CARB 2013 emission limits.

Keywords: Microturbine, NO_x emission, lean blowout limit, trapped vortex chamber, g load combustion, residence time

2.20.2 Introduction

Landfill gas represents a significant sustainable energy resource in California.⁵² There are over 3,000 known landfills in California. Currently over 300 of them remain active. Landfill gas (LFG) is produced as a result of anaerobic decomposition of organic wastes. The composition of the gas varies with the characteristics of the waste, age of the landfill, and weather conditions. Typically, LFG contains about 50 percent methane (CH₄), 45 percent carbon dioxide (CO₂), and other traces of gas such as nitrogen (N₂), oxygen (O₂), hydrogen sulfide (H₂S), and water vapor. The largest component of LFG, methane, is a potential energy source, but it is also an especially pernicious greenhouse gas (GHG). It is over 20 times as potent a GHG as CO₂. Methane emissions contribute significantly to global warming. They represented 5.7 percent of total GHG emissions (CO₂ equivalent units) in California in 2004. Agricultural activities (enteric fermentation and manure management) and landfills compose the major sources of these emissions. Accordingly, it is desirable to both recover the energy content of methane in LFG and to prevent the escape of unburned methane into the atmosphere. On-site distributed generation of electricity by LFG combustion in a microturbine is an attractive scalable technology for energy recovery and methane control. It is necessary, however, to control the level of NO_x (NO and NO₂) produced. NO_x is a potent air pollutant created at high temperature in the combustion process. Its rate of production is significant above 1800° K and doubles for every increase of 90° K. The need to control NO_x production will become much more severe when the California Air Resources Board's allowable limit of NO_x production drops in 2013

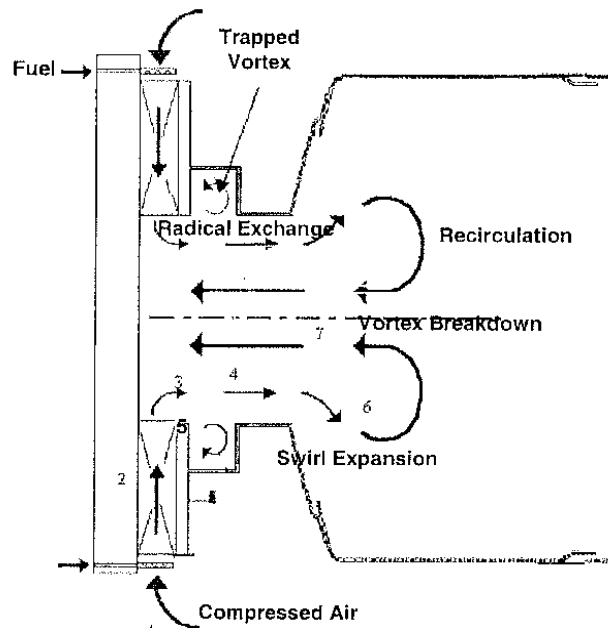
52 http://www.energy.ca.gov/2009_energy_policy/documents/2009-04-21_workshop/presentations/05-SCS_Engineers_Presentation.pdf

from 0.5 lb/MW hr to 0.07 lb/MW hr. This stringent limit on NO_x production is a problem that will limit the deployment of energy recovery from LFG unless a means is found to lower NO_x production.

The benefits to California ratepayers if the NO_x problem is solved are a significant increase in sustainable electricity production and a reduction in GHG emissions. California now has 67 landfill electricity projects that generate 274.7 MW. There are six projects under construction, which have the potential for 36 MW electricity and 35 candidate landfills of 118 MW potential. Collectively these projects have the potential for 429 MW of electricity production. The quantity of methane generated at a landfill depends upon the amount of waste placed, age of wastes placed, composition of wastes placed, and climate at the waste disposal site. Experts estimate methane emissions from California landfills to be 8.4 million tons CO₂ equivalent. Thus landfills comprise both a significant energy opportunity and a considerable source of GHG emission.

The advancement of science proposed in this project was to control NO_x production in LFG combustion in microturbines by a combustion chamber modification, the high g load combustor concept, shown schematically in Figure 21. The researchers designed this modification, a type of trapped vortex chamber (TVC), to enable a microturbine to run in the extreme lean limit of air to fuel ratio and thus lower flame temperatures. This reduces NO_x emissions. To minimize production of thermal NO_x it is necessary to design a combustor's primary zone so that the fuel and air react at a relatively low temperature. However at the extreme lean limit the flame becomes unstable, leading to lean blowout (LBO) conditions. TVCs have been investigated by a variety of researchers to improve flame stability. Typically this concept has employed a recess built either into the wall of a duct or downstream of a bluff body and equipped with a plurality of fuel and air supply holes. One or more vortical structures are established inside the cavity and circulate the fuel and air, establishing low velocity, high residence time combustion. The concept proposed here combined a TVC with a high g load fluid exchange mechanism. The term "high g load" refers to combustion taking place where a large body force established by fluid (gas) rotation and centrifugal effects serves to promote fluid exchange into and out of the trapped vortex cavity. The improved exchange between burned and unburned gas in a stable vortex promotes greater flame stability and lowers the LBO limit.

Figure 21: Schematic of the High G Load Combustor Concept for Flame Stabilization



2.20.3 Objectives

The goal of this project was to determine the feasibility of an advanced combustor concept (g load concept) to burn low BTU biogas fuels to exceed the CARB mandated 2013 emissions limits by 30 percent for microturbine applications. The researchers established the following project objectives:

1. Design a modular rig that simulates Ingersoll Rand's microturbine (MT250) combustor. Match the flow number of the inlet section within 5 percent of the MT250. Deliver drawings of hardware with critical dimensions and tolerances. Demonstrate that the rig is capable of 3500 g's using Penn State Combustion Lab facilities.
2. Fabricate a test rig. Deliver photographs of fabricated hardware. Prepare inspection report to demonstrate 100 percent compliance to design.
3. Conduct CFD (computational fluid dynamic) analysis of the test rig. Calculate g load profile with one of three swirler vane configurations with the proposed TVC feature as well as base case of MT250. Compare profile quantitatively with Objective 1 design above. Evaluate effect of inlet swirl angle on g load. Compare profile with Objective 1 design.
4. Conduct reacting test. Determine overall combustor performance as a function of g loading for two power loads of 75 percent and 100 percent. Performance goals are LBO limit < 75 percent power with ISO day conditions, sea level altitude; emissions goal is

NO_x, CO, unburned hydrocarbons < 70 percent CARB 2013 limits at one swirler configuration; and combustor efficiency goal is > 98 percent at 75 percent power.

5. Characterize the flame structure. Employ various flow conditions and g loads. Understand the effect of g load and TVC on overall combustor performance. Compare images of actual flame features with predictions of Objective 3 CFD analysis. Produce and document validation data for future CFD analysis of reacting case to optimize microturbine design.

2.20.4 Outcomes

1. The researchers designed a scaled modular test rig that modeled an Ingersoll Rand MT70 microturbine combustor. They determined that the MT250 combustor inlet temperature made modulation of airflow into a trap cavity difficult with high reliability, low cost valves. The researchers presented hardware drawings of the test rig. Analysis confirmed g load range from 770 to 5050 g.
2. The researchers fabricated a test rig and presented photographs of the fabricated hardware. Inspection demonstrated design compliance to within 1/1000 inch.
3. The researchers conducted a CFD analysis of the test rig using a commercially available numerical code. They calculated g load and cold flow field in the inlet section of the combustor at various flow conditions and modified the test rig to achieve the g load ranging from 770 to 5050 g over the range of mean velocity. They evaluated the effect of g load on results but did not present them as an explicit function of swirl angle.
4. Reacting tests demonstrated that the TVC extended the LBO limit to lower equivalence ratio up to 5 percent for all cases when compared with cases without TVC. Actual NO_x emission measurement results showed NO_x emission consisted mostly of NO₂. The corresponding reduction of NO_x emission to the extended LBO limit was as much as 30 percent. Researchers did not make explicit comparison with CARB limits or as function of power. Neither did they give combustor efficiency.
5. Studies of mapped flame images identified the range of operating conditions. The flame resided in the trapped vortex chamber when the equivalence ratio was near the lean blowout (LBO) limits.

2.20.5 Conclusions

1. The researchers successfully designed a scaled modular test rig that modeled an Ingersoll Rand MT70 microturbine combustor.
2. The researchers successfully fabricated a test rig suitable for testing.
3. CFD analyses of the test rig allowed calculation of g load and cold flow field in the inlet section of the combustor at various flow conditions. It guided modification of the test rig to achieve the g load ranging from 770 to 5050 g over the range of mean velocity. The researchers evaluated the effect of g load on results, but did not present results as an explicit function of swirl angle. Thus they only partially met this objective.

4. Reacting tests indicated that the TVC extended the LBO limit to lower equivalence ratio up to 5 percent for all cases when compared with cases without TVC. However the LBO limits were found to increase as g loads increased, indicating the increase of turbulent velocity with respect to g load in the TVC found by earlier workers was not the reason for the extension of LBO limits. Importantly, researchers found that the LBO limits decreased as the residence time increased for all g load vanes, suggesting the improvement of LBO limits was mainly due to the increase of residence time of mixture in the TVC.
5. Studies of mapped flame images identified the range of operating conditions. Researchers found that the flame resided in the trapped vortex chamber when the equivalence ratio was near the lean blowout (LBO) limits.

Overall the trapped vortex chamber extended the lean blowout limits to marginally lower levels. This would enable operation at lower equivalence ratios, reducing NO_x emissions. The objectives of this research program were therefore achieved. It was not proven that this design will meet the CARB 2013 emission limits when burning LFG or digester fuels.

2.20.6 Recommendations

Since residence time has a greater beneficial influence on extending the lean blowout limit over g loading, it would be useful to refocus the modeling and experimental program in that direction. In particular, it would be useful to vary the dimensions of the experimental TVC annulus (outer diameter, length, inner surface topography), estimate residence times, and measure lean blowout limit. The researchers propose useful *particle image velocimetry (PIV)* measurements to determine the velocities and residence time in the trapped vortex chamber (TVC). They should conduct these determinations over a variety of TVC shapes as indicted above.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.20.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system

- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California electricity supply, transmission, and distribution system. The benefits to California ratepayers if the NO_x problem is solved are significant increase in sustainable electricity production and concomitant reduction in GHG emissions. California now has 67 landfill electricity projects which generate 274.7 MW. There are six projects under construction which have the potential for 36 MW electricity and 35 candidate landfills of 118 MW potential. Collectively these projects have the potential for 429 MW of electricity production. Although landfills have methods of controlling methane emissions, the researcher estimated that California landfills produce 8.4 million tons CO₂ equivalent. Thus landfills comprise both a significant energy opportunity and a considerable source of GHG emission.

2.20.7.1 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.20.7.2 Marketing/Connection to the Market

The researchers discussed the use of this innovation with Ingersoll Rand Energy Systems. The goal is to use the technology in gas turbine engines in the range of 100 kW to 300 kW. If the researchers and manufacturing partner were to be the first to demonstrate compliance with CARB 2013 emission limits, it would give them a commercial advantage.

2.20.7.3 Engineering/Technical

The researchers stated that the technology must work over a wide ambient temperature range, and must accept a wide range of gas compositions. While the researchers did not have a firm post-project development plan, they estimated that additional work would take about one year.

2.20.7.4 Legal/Contractual

The researchers have submitted patent application #20080271703.

2.20.7.5 Environmental, Safety, Risk Assessments/ Quality Plans

Issues of environment, safety, risk assessment/ quality arising from the modification of a commercial microturbine to include a TVC do not seem to be serious at this point.

2.20.7.6 *Production Readiness/Commercialization*

It is premature to forecast commercialization readiness until all technology issues have been resolved.

2.21 **Novel Heat Exchanger Fin Surface Design for Improved Condensate Management**

Awardee: Miami University

Principal Investigators: Andrew Sommers

2.21.1 Abstract

The goal of this project was to assess the effectiveness of heat exchangers constructed using anisotropic aluminum fins to drain more completely the condensate that forms on the heat transfer surface during normal operation. The aim was to improve the thermal hydraulic performance of the heat exchanger. The researchers prepared two prototype fins with micro-channels nominally 15 μm wide (Coil 2) and 50 μm wide (Coil 3) designed to provide directional flow paths for condensate. They coated the fins with alkyl silane to promote hydrophobicity. The researchers tested the prototypes for critical sliding angle, water retention, and air side pressure drop and demonstrated improved performance over both the base case (Coil 1) and a coil homogeneously modified with oxygen plasma (Coil 4). Potential energy savings projected for the proposed technology proved to be significantly less than anticipated. Manufacturing costs were not addressed nor were net benefits resulting from the proposed technology.

Keywords: Micro groove, anisotropic fins, hydrophobic, heat exchangers, air conditioning, condensate management

2.21.2 Introduction

Heat exchangers play a significant role in the overall efficiency of heating, ventilation, air conditioning, and refrigeration (HVAC&R) systems. They are inherently susceptible to buildup of condensate, which hinders their performance. Water retention on the air side of liquid to air heat exchangers reduces the sensible air side heat transfer coefficient, increases the core pressure drop, and provides sites for biological activity. Although research has investigated surface wettability for other applications, this research has not yet been applied to HVAC&R systems.

The proposed technology involved modification of the surface of heat exchanger fins to maximize hydrophobicity and to provide a directional flow path to remove excess condensate. Typically heat exchanger fins are constructed from aluminum or copper. These metals may be treated chemically to increase hydrophobicity. The researchers additionally used a

The researchers were able to demonstrate improved performance by incorporation of micro-channels in combination with an alkyl silane coating. Although both Coils 2 and 3 were superior to the base case in nearly every test, Coil 2 provided the most potential for energy savings in a lower air velocity installation, and Coil 3 provided the most potential for energy savings in a large commercial setting. A typical residential installation could realize an annual cost savings of approximately \$10 to \$25 per HVAC unit. Large scale commercial installations could realize annual cost savings of approximately \$100 yearly per HVAC unit. Manufacturing costs were not specifically addressed, but they are likely to be prohibitive to adoption of this technology.

Table 7: Comparison of the Various Assessment Methods

For untreated surfaces and heat exchangers (Goal: To be more hydrophilic)	
Apparent contact angle	Coil #2 > Coil #3 > Coil #1
Contact angle hysteresis	Coil #2 > Coil #3 > Coil #1
Water retention in dip testing	Coil #2 > Coil #3 > Coil #1
For treated surfaces and heat exchangers (Goal: To be more hydrophobic and drain more water)	
Apparent contact angle	Coil #3 > Coil #1 > Coil #2 > Coil #4
Contact angle hysteresis	Coil #3 > Coil #1 > Coil #2 > Coil #4
Critical inclination angle	Coil #4 > Coil #2 > Coil #3 > Coil #1
Water retention in dip testing	Coil #2 > Coil #3 > Coil #1 > Coil #4
Wet pressure drop	Coil #3 > Coil #2 > Coil #4 > Coil #1

Note: Arranged from Best to Worst with the Best Performer shown in **BOLD**

2.21.3 Objectives

The goal of this project was to prove the feasibility of using relatively inexpensive manufacturing techniques to produce non-homogenous, chemically modified aluminum surfaces to more effectively manage condensate on heat exchanger fin stock. If successful, the technology would increase the effectiveness of heat exchangers to more completely drain the condensate that forms on the heat transfer surfaces during normal operation. The net result would be improved thermal hydraulic performance of the heat exchanger. The researchers established the following project objectives:

1. Confirm the channels on the fin samples all have the same dimensions to within $\pm 1 \mu\text{m}$ to ensure they all have the same micro-channel dimensions to eliminate extraneous surface effects.
2. Verify that the goniometer is capable of measuring critical contact angles to within ± 1 percent in order to show that the Ramé-Hart precision contact angle goniometer used for these measurements is capable of resolving small changes in surface wettability.
3. Establish the contact angle and critical inclination angle data of the baseline surface for future comparison with an error of less than ± 5 percent to build a criterion to assess the change in the contact angle for the enhanced surfaces.

4. Verify that the inclination angles of the baseline surface are greater than 30° for the volumes of droplets less than $50\ \mu\text{L}$ to demonstrate a high propensity for water retention on the baseline surface.
5. Establish enhanced data for the novel surfaces with an error of ± 5 percent and verify that the required critical inclination angle for sliding is less than the baseline surface.
6. Demonstrate the repeatability of steady state water retention on heat exchanger coils to within ± 3 percent to establish a criterion for assessing changes in overall water retention for the prototype coils.
7. Show that the steady state water retention on the prototypes decreases by at least 10 percent.
8. Demonstrate that the velocity profiles are fully developed to ensure consistent test conditions for all pressure drop experiments.
9. Demonstrate that the velocity profiles are flat to within ± 8 percent for the highest test velocity to ensure consistent test conditions for all pressure drop experiments.
10. Confirm that the wet coil pressure drop decreases by at least 10 percent to show a reduction in condensate retention and decreased fan power requirements and thus energy consumption.
11. Confirm that the projected savings from using the enhanced fin surface in heat exchangers in air conditioning systems is greater than \$100/yr at \$0.095 per kilowatt hour.

2.21.4 Outcomes

1. The researchers created two micro-groove aluminum structures using photolithography and identified them as Coil 2 and Coil 3, with nominal channel widths of 15 and $50\ \mu\text{m}$, respectively. They measured channel dimensions using a surface profilometer. For Coil 2 micro-channel width and depth measurements were $14.877 \pm 0.364\ \mu\text{m}$ and $9.561 \pm 1.405\ \mu\text{m}$, respectively. For Coil 3 micro-channel width and depth measurements were $49.838 \pm 1.029\ \mu\text{m}$ and $15.953 \pm 1.956\ \mu\text{m}$, respectively.
2. The stated accuracy of the goniometer was $\pm 0.1^\circ$. The researchers identified other sources of error, including evaporative losses that would contribute to accuracy estimated to be $\pm 1\%$.
3. The researchers measured the advancing contact angles and the receding contact angles for four different coils. The variations in the measurements of the advancing angle ranged from 1.5 percent to 4.96 percent, while the variations in the measurements of the receding angle ranged from 5.37 percent to 15.1 percent.
4. The researchers measured the critical sliding angle for the baseline surface using droplets ranging in size from 20 to $70\ \mu\text{L}$ by recording photographic images during

continuous inclination of a tilt table. The critical sliding angle for droplets less than 50 μL ranged from 40° to 70° , with larger angles corresponding to smaller droplet sizes.

5. Researchers repeated testing for Objective 4 for each of the three modified prototype surfaces. Critical sliding angles were larger for the baseline than for the treated prototypes at all droplet sizes below 60 μL . The researchers did not discuss errors introduced during critical sliding angle measurement.
6. The researchers performed dynamic dip testing five times for each surface and determined the water retention volumes as a function of time. They presented results as averages \pm measurement errors for each surface tested. Measurement errors ranged from 3 percent to 9.6 percent, with an average error of 5.9 percent.
7. The researchers determined steady state behavior existed at 25 minutes. At this point the average water retention for Coil 1 (baseline), Coil 2 (15 μm channels), Coil 3 (50 μm channels), and Coil 4 (oxygen plasma) were 37.7 g, 23.2 g, 27.2 g, and 43.7 g, respectively. Coil 2 and Coil 3 decreased water retention by 38.5 percent and 27.9 percent, respectively. Coil 4 increased water retention by 16.1 percent as compared to the baseline.
8. The researchers measured the velocity profile using Pitot tubes spaced at 0.5 inch intervals across the wind tunnel. The velocity profile at 285 CFM was uniform and fully developed to within 0.25 inches of the tunnel wall.
9. Flow rates within the wind tunnel were consistent to within 1 percent vertically and 2 percent horizontally at a flow rate of 285 CFM, with the exception of the outermost 0.25 inches of the tunnel.
10. The researchers plotted the change in pressure drop between dry and wet conditions against flow velocity. When compared to the baseline Coil 1, the pressure drop was at least 10 percent smaller for Coil 3 at flow rates less than or equal to 200 CFM. For Coil 4 the pressure drop was 10 percent smaller at flow rates less than 100 CFM. Coil 4 performed similarly to the baseline case.
11. The researchers calculated the expected annual energy savings for Coil 2 and Coil 3 by summing the savings due to a reduced pressure drop and the savings due to reduced latent heat. Savings due to the reduced pressure drop increased with air flow velocity. Total savings ranged from \$11.43 to \$25.44 per coil per year for air velocities ranging from 50 to 20,000 cfm and operating at 1000 equivalent full load hours (EFLHs) for Coil 2. Savings for Coil 3 ranged from \$8.39 to \$30.05 per coil per year for the same velocity range and capacity. Note that 20,000 CFM is a typical intake for a large commercial building. The researchers doubled the calculated savings to represent a dual coil evaporator unit, resulting in a projected savings of \$50.88 for Coil 2 or \$60.10 for Coil 3 installed in a commercial facility. Further, the researchers doubled the operation capacity to 2000 EFLH to represent four months of continuous operation per year. For a

commercial facility at this higher capacity, projected savings would be \$78.92 for Coil 2 or \$103.44 for Coil 3.

2.21.5 Conclusions

1. The researchers did not meet the objective to ensure dimension uniformity within ± 1 μm . Although width measurements for both prototypes and depth measurements for Coil 2 met the criteria, depth measurements for Coil 3 were within approximately ± 2 μm . The researchers hypothesized that the longer etching time required to create channels on Coil 3 may have resulted in the larger standard deviation.
2. The researchers met the objective to verify goniometer accuracy to within 1 percent. However there did not appear to be any scientific basis for the determined accuracy. Rather, it was estimated by the researchers.
3. The researchers met the objective to measure advancing angles to within a 5 percent error (4.96 percent maximum error measured). However, receding angle error measurements ranged from 7.19 percent to 15.1 percent, exceeding the project objective. The error was larger due to the small angles being measured.
4. The researchers met the objective to demonstrate a high propensity for water retention on the baseline surface.
5. The researchers met the objective to verify that the critical sliding angle was less for the prototypes than the baseline for droplets smaller than 60 μL . For larger droplets, differences in the critical sliding angle between the tested surfaces were insignificant due to the dominance of gravitational forces at steep angles.
6. The researchers did not meet the objective to demonstrate repeatability of steady state water retention within an error of 3 percent. The researchers suggested that the larger error margin was due to differences in dropping velocities between tests.
7. The researchers met the objective to demonstrate a decrease in water retention by at least 10 percent for the two prototypes modified to include micro-channels. Although the prototype treated with oxygen plasma actually increased water retention, it did not include the proposed micro-channel technology. Because it did not include the proposed technology, it is unclear why it was included in this study.
8. The researchers met the objective to demonstrate a fully developed velocity profile at the highest test velocity.
9. The researchers met the objective to demonstrate a consistent velocity profile at the highest test velocity.
10. The researchers met the objective to confirm that the wet coil pressure drop decreased by at least 10 percent for the prototypes with micro-channels. The prototype without micro-channels performed nearly the same as the base case. However it could not be used in evaluating achievement of the objective, since it did not include the proposed technology.

11. The researchers were unable to meet the objective to confirm a projected savings of greater than \$100 per year for a typical installation. Although they projected savings for Coil 3 in excess of \$100 per year, this was only for the highest flow rate, representative of a large commercial facility operating under fairly extreme conditions with continuous occupancy. None of the estimates for residential or small to mid-sized commercial or retail usage would result in cost savings in excess of \$100 per year for Coil 3. Even the extreme case presented for Coil 2 did not exceed \$100 per year in savings.

2.21.6 Recommendations

The researchers were able to demonstrate improved performance of anisotropic aluminum fins over the untreated isotropic surfaces, but they did not demonstrate cost effectiveness. The improved performance only led to modest projected savings as a result of the technology. The researchers did not assess the costs required to implement the technology, but they acknowledged that the current costs to manufacture the micro-channels was a comparative disadvantage of the technology.

As part of continued development of this technology, the Program Administrator recommends that the following tasks be completed:

1. Investigate manufacturing costs to evaluate the cost/benefit of the proposed technology.
2. Evaluate the durability of the etched channels after cycle testing over an extended period.
3. Perform a life cycle analysis for the technology.

2.21.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. The researchers estimated that the proposed technology could lead to a \$10 to \$25 yearly savings per installation in a typical residential HVAC&R unit. Commercial installations could be expected to realize a greater savings, potentially as much as \$103 per installation for large commercial applications in warm climates. The researchers did not investigate the incremental cost of the technology over typical heat exchanger manufacture. Therefore the net benefit cannot be determined.

2.21.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.21.8.1 *Marketing/Connection to the Market*

The researchers have not yet performed a market analysis. They have exposed the technology to selected HVAC&R manufacturing companies. Although the technology could serve all consumer markets, it is best suited to large scale industrial and commercial applications due to the larger potential energy savings associated with larger cooling needs.

2.21.8.2 *Engineering/Technical*

The researchers have not constructed a development path to a product. They anticipate that product development will take two to five years.

2.21.8.3 *Legal/Contractual*

The researchers do not intend to apply for patent protection. They have published "a few conference papers." It is their intent to put the intellectual property developed in this project into the public domain.

2.21.8.4 *Environmental, Safety, Risk Assessments/ Quality Plans*

Environmental, Safety, Risk Assessments, and Quality Plans have not yet been developed. Health concerns will likely focus on chemicals required to perform surface etching.

2.21.8.5 *Production Readiness/Commercialization*

The researchers have not yet developed a commercialization plan and will need external support to pursue commercialization.

2.22 Algae Biomass Gasification

Awardee: QuantumSphere Inc.

Principal Investigators: Sterling Harris

2.22.1 Abstract

The purpose of this project was to explore the feasibility of converting selected high carbohydrate, high growth rate algae strains into hydrogen and carbon monoxide syngas via sub-critical and super-critical water oxidation (SCWO) at low temperatures and modestly high

pressures. The reaction is aided in part by the presence of a high surface area standard industrial Raney nickel catalyst. Because Raney nickel by itself tends to favor methane production, it was used as a support for nanometer size tin particles. The researchers selected the algae species *Chlorella vulgaris* and *Scenedesmus dimorphus* both for their density (3.2 and 8.7 grams per liter, respectively) and their carbohydrate to dry mass ratios (.094 and .124, respectively). The researchers also processed various sugars at sub-critical and super-critical conditions in the presence of the catalyst to determine a baseline best case scenario for aqueous phase carbohydrate reforming. The researchers prepared a preliminary design for a pilot plant capable of producing 1,000 cubic feet per day of syngas. The total power required to operate that pilot plant was approximately 403 kW. The total land required to grow a sufficient amount of algae for that plant would be 10 acres. The project did not demonstrate technical feasibility because of negative net energy requirements.

Keywords: Aqueous phase reforming, biomass, algae, gasification, hydrogen, syngas, Raney nickel, nanometer tin, biogas

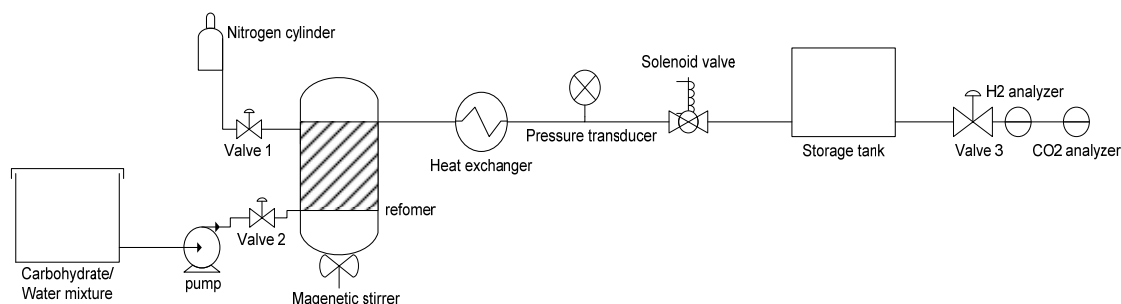
2.22.2 Introduction

Expanding the use of biomass is an important policy goal for the State of California. In addition to producing biodiesel from animal fats and vegetable oils and direct use of biomass in power plants, numerous high volume amounts of biomass remain underutilized. The use of other biomass sources has created perceived conflicts with food streams, for example corn based ethanol. Expanding the use of biomass will require increasingly creative methods for growing and converting biomass to energy.

Algae are a source of biomass receiving considerable attention, in part because of their fast growth properties. Most attention in the literature has been focused on using algae as a source of lipids (oils) for ultimate conversion to biodiesel. Extraction of lipids is a valuable source of energy products, but leaves behind potentially valuable residues, including simple and complex carbohydrates.

In this project researchers investigated the feasibility of gasifying algae's carbohydrates to produce hydrogen and syngas. Figure 24 shows the process and instrument diagram of the equipment used to perform these tests.

Figure 24: Process and Instrumentation Diagram for the Gasification of Glucose



2.22.3 Objectives

The goal of this project was to demonstrate the feasibility of gasifying the carbohydrate fraction of algae biomass. The researchers established the following objectives:

1. Identify those algae species with high carbohydrate content and high growth rates and determine the optimal growth conditions for each particular species. Create preliminary designs of an algae photo-bioreactor (PBR) and a gasification reactor, including sub-critical water generator. The researchers hoped to attain an algae doubling rate (2X) every eight hours and sub-critical water system energy consumption of 500 kJ/liter of water.
2. Select design points for algae gasification. The goal was a three stage system with total system energy input of 550 kJ/kg of algae biomass.
3. Fabricate a gasification reactor to convert wet algae to biogas with an efficiency goal of 60 percent conversion to methane and/or hydrogen. Create a laboratory scale plant for 10 cubic feet/day of biogas production from wet algae and a photo-bioreactor for growing sufficient mass of algae to yield the above gas generation rate.
4. Optimize the technology for methane production as well as integration of recycled waste gas (hydrogen and CO) for oxidation of process energy input with an energy output goal of 2000 kJ/kg of algae processed.
5. Design a large scale pilot plant with an economic cost goal of biogas equal to combined natural gas (~\$12.00 MMBtu).

2.22.4 Outcomes

1. The researchers selected *Chlorella vulgaris* and *Scenedesmus dimorphus* because of their 12.5 percent and 9.7 percent carbohydrate content (by dry weight), respectively, and a growth period of 60 days with a density of .8 grams/liter. The researchers obtained maximum growth rate of roughly 90 percent per 24 hours, with a sub-critical water system energy consumption of roughly 650 kJ/liter of water.
2. The researchers designed a three stage system with a total system energy input of approximately 650 kJ/kg of algae biomass. They did not assume nor measure an initial drying step before the algae were processed.
3. The researchers designed and fabricated a laboratory scale plant capable of producing 1.5 cubic feet of biogas per day from algae biomass. They designed and fabricated three photo-bioreactors and supplied the reactors with enough algae to conduct numerous test runs, but not enough algae to run the reactor continuously. The researchers did not process the lipid portion of the algae, although it was substantial in terms of percentage of dry weight, because more efficient use could be made of this material in the direct production of liquid biodiesel. Such a process would require considerably less heat and pressure and thus require less energy.
4. The researchers optimized production of hydrogen rather than methane because hydrogen is a much higher value product gas and because the process led to low overall

gas yields compared to the energy required to reform the algae biomass. The researchers measured the total energy output at 5.92 kJ/kg of algae processed.

5. The researchers originally estimated the cost target for the production of 1000 cubic feet of biogas at \$12. However, they measured the cost of running the pump and heater as well over \$1,000 to produce 1,000 cubic feet of gas.

2.22.5 Conclusions

Assuming the hydrogen produced from this process is used in a PEM fuel cell (greater than 50 percent efficient), the total amount of electricity produced on a continuous basis would amount to about 4 kW. Compared to the more than 404 kW of electricity required to produce the hydrogen, the process is neither energy nor economically efficient despite the relatively high conversion rate achieved.

Hydrogen production from algae alone is limited by the low carbohydrate fraction of the total dry mass. An alternative might be to take advantage of the high lipid content, produce some type of biodiesel upstream, and then send the remaining effluent to a bio-gasification facility. However the problem of heating a substantial amount of water would remain.

This research project demonstrated that at low reaction temperatures economical quantities of hydrogen cannot be produced from algae even in the presence of a catalyst. This technology has a number of technical hurdles to overcome before it can compete with conventionally produced syngas or hydrogen.

2.22.6 Recommendations

The researchers should evaluate the use of this technology in a staged cascade processing of algae biomass with early step removal of lipids and other constituents, leaving carbohydrate gasification to the last or near last step when carbohydrates are more concentrated. The researchers should investigate the use of concentrated solar energy to provide heating and/or pumping requirements to improve the net energy balance.

2.22.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research would be from reduced environmental impacts of the California energy supply and distribution system. In this project, while bio-hydrogen was produced by algae gasification through sub-critical water reforming, no biomethane was produced. The practical benefits to the State of California cannot be quantified

until an integrated hydrogen pathway for storage and distribution exists and the net energy balance issue is resolved.

2.22.7.1 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.22.7.2 Marketing/Connection to the Market

The researchers found the concept has a negative net energy balance, and they do not anticipate marketing the concept further.

2.22.7.3 Engineering/Technical

The researchers have determined that further engineering and technical development is not cost effective or energy efficient.

2.22.7.4 Legal/Contractual

The researchers have not identified a patentable technology and have indicated they will not develop the concept further.

2.22.7.5 Environmental, Safety, Risk Assessments/ Quality Plans

Unless the researchers pursue alternative engineered strains of algae, there are no known environmental or safety risks. Quality plans are premature until the researchers resolve the net energy issue described above.

2.22.7.6 Production Readiness/Commercialization

The technology is not ready for commercialization.

2.23 Reducing Natural Gas Consumption by Modifying Containers of Water Heaters

Awardee: Auburn University

Principal Investigators: Jay M. Khodadadi

2.23.1 Abstract

The goal of this project was to demonstrate reduced residential gas water heater fuel consumption (at least 5 percent) through the use of a low cost internal (water side) baffle. The research employed extensive computational fluid dynamics and computer aided engineering modeling. Variation of the total surface heat flux on the flue gas pipe was an important determining factor for placement of the baffle. The location of the baffle corresponded to the position of high values of the total surface heat flux. In addition, the researchers determined the role of the inlet water swirl element in the top inlet/top outlet unit and its effect on flow asymmetry and the overall flow pattern. The results for the second baffle design correspond to a natural gas consumption savings of 4.31 percent to 5.6 percent over the two tests conducted. A water heater manufacturer estimated manufacturing costs for production of 10,000 to 100,000 annual units to be roughly \$3 per unit.

Further refinement of the design and consideration of its use in commercial size heaters in collaboration with a manufacturing partner are appropriate next steps.

Keywords: Baffle, gas water heater efficiency, swirl, heat transfer, extended surface, computational fluid dynamics, computer aided engineering, turbulence modeling

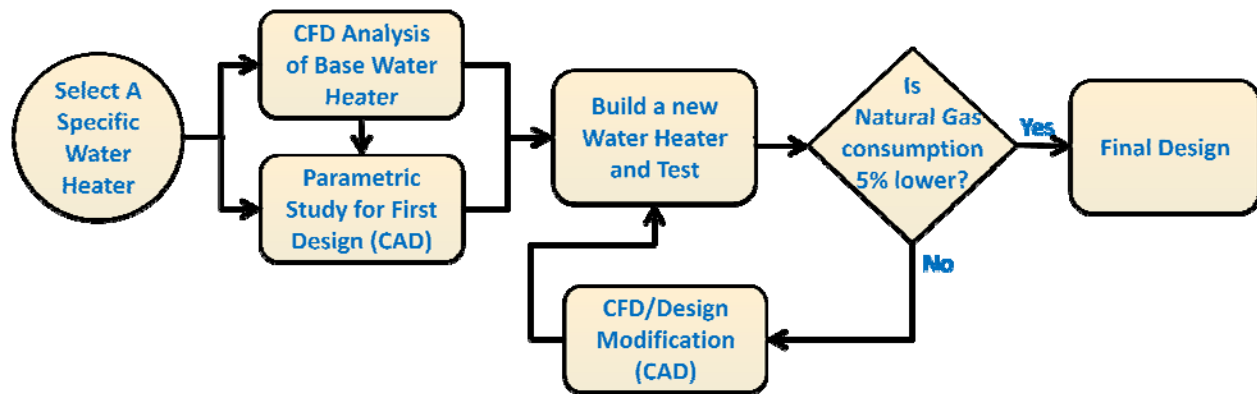
2.23.2 Introduction

Substantial improvements have been made in the efficiency of natural gas fired water heaters as a result of California's leadership in promulgating aggressive standards. However, gas consumption for domestic water heating remains one of the larger contributors to total customer bills.

Further cost effective improvements in efficiency could provide savings to customers and reduce emissions in California. For example, a 5 percent reduction in gas usage could provide roughly \$10 in annual savings for a typical residential customer.

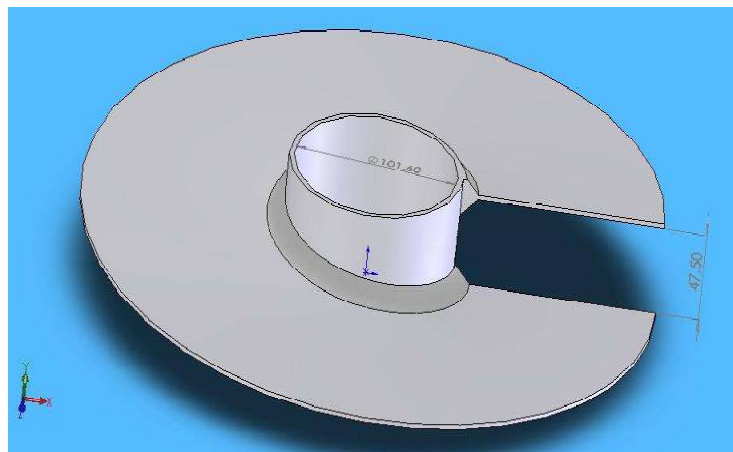
The researchers in this project conducted computer aided engineering (CAE) analyses of a specific water heater and its modifications to determine a better design based on the criterion of greater natural gas savings. This approach is summarized using a flowchart in Figure 25.

Figure 25: Flowchart Showing the General CAE Approach Adopted Throughout the Project



The researchers demonstrated that an internal baffle, a roughly 10 inch metal plate shown in Figure 26, could provide a 5 percent reduction in natural gas usage, and it is likely that additional refinement could further increase savings. A manufacturer of water heaters collaborated in fabrication and testing and estimated that a baffle could be included for less than three dollars in added manufacturing costs. The researchers conducted intensive computational fluid dynamics modeling and design, followed by fabrication and testing of an evolved baffle design in two typical residential water heaters. While this research focused on residential water heaters, there is every reason to believe that similar savings could be realized in larger heaters for commercial applications.

Figure 26: First Baffle Design



The first design was approximately 14 inches in diameter and featured a helical extended surface welded to a collar that was placed on the outside surface of the pipe that separates the hot gas from the water.

After initial modeling and testing, the researchers and the water heater manufacturer decided to change the target water heater from a side inlet/outlet model to a top inlet/outlet model which

has a larger share of the water heater market. Further extensive CFD modeling yielded a detailed view of flow, combustion, and heat transfer in the target model.

2.23.3 Objectives

The goal of this project was to determine the feasibility of reducing a typical residential water heater's natural gas consumption by attaching a simple ring-like baffle to the inside wall of its tank, thereby increasing the amount of heat absorbed. The researchers established the following project objectives:

1. Demonstrate that the sensors to be used in laboratory testing would measure gas/water flow rates and temperatures (GWFT) with an error of +/- 5 percent.
2. Demonstrate working of a test candidate water heater under governing industry protocols,⁵³ and verify that the gas/water flow rate and temperature measurements were within +/- 10 percent of specifications given by a manufacturer of water heaters.
3. Demonstrate that the computational fluid dynamics (CFD) calculations for a base (unmodified) water heater match measured GWFT within +/- 15 percent.
4. Model and design a first candidate baffle and demonstrate through CFD calculations that it increased heat absorption during the heat up cycle by at least 1.5 percent over the no baffle design.
5. Demonstrate that the CFD predicted results, including performance improvements, matched GWFT measurements in the first candidate within +/- 15 percent.
6. Model and design a series of six incrementally improved baffles, each with a projected increase in heat absorption during heat up of at least 1 percent over the prior design.
7. Demonstrate that CFD predictions matched GWFT measurements in heaters built with baffle designs two through six (from the step above) with an error +/- 15 percent.
8. Confirm that the natural gas savings for the best baffle design was at least 5 percent compared to the no baffle design.
9. Confirm that the best baffle design would add less than \$20 to manufacturing cost.

2.23.4 Outcomes

1. Testing at the research laboratory of a water heater manufacturer confirmed that measurements of natural gas and water flow rates, as well as temperature measurements at various locations, were within +/-2 percent.

53 See Code of Federal Regulations, Title 10-Energy, Chapter II, Department of Energy, Subchapter D – Energy Conservation, Part 430 – Energy Conservation Program for Consumer Products, Subpart B – Test Procedures, Appendix E – Uniform Test Method for Measuring the Energy Consumption of Water Heaters

2. The tested 40 gallon side inlet/outlet water heater performed as expected through a series of DOE protocols for 1 hour and 24 hour test periods.
3. Early comparisons of predicted and measured results did not fully meet the +/- 15 percent goal and led to a decision to modify the modeling approach to account for water density variations as a function of temperature. Using this approach yielded a maximum observed deviation of 6.66 percent at a single thermocouple location.
4. The first baffle design was a helical extended surface welded to a collar attached to the gas/water pipe's outer surface as shown in Figure 25. Model results showed an increase in heat extraction of 4.2 percent over the standard no baffle design.
5. The researchers did not present results comparing the calculated results from Objective 4 with the baseline results from Objective 3 as originally called for. Instead, they stated that concerns about original heater modeling and test heater fabrication compromised completion of this objective.
6. The researchers designed a second, smaller baffle. This baffle had a diameter of 10 inches, compared to the first design's 14 inches, and a thickness of one-eighth inch, compared to the first design's one-tenth inch. CFD calculations indicated that the second design offered a 6.4 percent improvement in absorbed heat over the no baffle design. The researchers did not conduct additional cycles of design/testing (for a total of six) called for in this Objective. According to the researchers, this was because the second design's calculated performance already met the overall objective of a 5 percent reduction in natural gas consumption.
7. The researchers did not include data confirming that CFD predictions match GWFT measurements for the two (originally to be six) baffle designs within +/- 15 percent as called for in this Objective. However they did present test results showing that the first design demonstrated a 1.25 percent improvement in thermal efficiency over the standard water heater, and the second design demonstrated an improvement ranging from 3.31 percent to 4.34 percent.
8. The results for the second baffle design correspond to a natural gas consumption savings of 4.31 percent to 5.6 percent over the two tests conducted.
9. The water heater manufacturer estimated manufacturing costs for production of 10,000 to 100,000 annual units to be roughly \$3 per unit.

2.23.5 Conclusions

This research met the most important of its objectives.

1. The measurements were well within the objective's tolerance band.
2. The calculated temperatures were within 6.66 percent of the actual. This is better than the objective of +/- 15 percent.

3. While this objective was met, the decision to switch to a top inlet/outlet model slowed progress but provided a path to potential application in the most widely accepted market segment.
4. The modeled increases were 4.2 percent and 6.4 percent, well above the objective of 1.5 percent.
5. No conclusion could be drawn for this objective, since the required testing was not performed, as explained in Outcome 5 above.
6. The second design's improvement over the first exceeded this objective, despite having a smaller surface area. This indicated that the baffle's influence over the flow field was important in addition to its role as an extended heat transfer surface. Although the second design met the overall gas savings objective for the research, stopping the design/test cycles at this point precluded the opportunity to search for greater savings in the (funded) design/test cycles three through six.
7. The test data presented for this objective show measured performance improvements for the two baffle designs that met the fuel saving objectives of the research. However, the absence of data for predicted vs. measured results, similar to their absence in Objective 5, leaves the full validation of the CFD model unclear.
8. The test data supported a natural gas savings very close to the objective and certainly indicative of the baffle design's promise.
9. The cost estimate for a commercial scale baffle suggested this could readily be incorporated in future designs.

2.23.6 Recommendations

The researchers' suggestion that the tests conducted for this proposal be duplicated/checked by an independent third party made sense, as does conducting additional testing for performance under varying operating conditions and for long term reliability. If the successful results in this research are confirmed, the logical next step would be moving to a commercial rollout of water heaters employing an optimized baffle. This could be accomplished through a licensing agreement, possibly including one described by the researchers between Auburn University's Office of Technology Transfer and the project's industrial collaborator.

Since domestic water heaters are covered by various plumbing and building codes, it is important to establish that the addition of a baffle does not impact code compliance and product quality when the innovation is commercialized. In addition, the researchers should establish that the baffle does not impact the functional lifetime of the water heater in areas of California that have potable water with high mineral content (e.g., Southern California).

2.23.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of energy in California. The drivers of potential savings in natural gas consumption would be the actual efficiency improvement of this design over conventional water heaters and the penetration rate of heaters employing this design in new and replacement installations. Using typical estimates of residential gas consumption for water heating and assuming a 5 percent reduction for this design leads to a potential annual savings of roughly \$10 per customer for the new design, which could be partially offset by the one time added cost of the baffle, whose manufacturing cost is estimated to be less than \$3. Assuming a 10 year life for California's approximately 10 million such heaters, a potential annual market of one million units exists. Absent a change in efficiency standards, the relatively small individual savings may limit market penetration. However, given the large size of the annual replacement market, overall savings to California could be significant if scale were achieved. If an enhanced commercial water heater were offered with similar or better savings, there is potential for additional savings in this market as well.

2.23.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.23.8.1 *Marketing/Connection to the Market*

The researchers established a non-disclosure agreement with an unidentified industrial collaborator. A search of retail residential product offerings found no indication that a similar baffle design has been incorporated in currently available products.

2.23.8.2 *Engineering/Technical*

Unless the present baffle design is selected for commercialization, additional time and funding will be required to finalize an evolved design. This could require at least an additional 18 months and \$100,000.

2.23.8.3 Legal/Contractual

The researchers identified no apparent patent infringements. The patent application submitted in 2008 is currently under review. A non-disclosure agreement remains in effect with the industrial collaborator for prototyping and testing.

2.23.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

The researchers did not address these issues since their university has no plans to commercialize the technology directly.

2.23.8.5 Production Readiness/Commercialization

A final design has not been identified for commercialization. The industrial collaboration has not been identified.

2.24 Low Cost Parabolic Trough

Awardee: Randal Perisho

Principal Investigators: Randal Perisho

2.24.1 Abstract

This project demonstrated the potential feasibility of using a simple, low cost, modular solar parabolic trough design. At the beginning of this project the standard was a utility scale trough for solar thermal systems. The new modular parabolic trough concept targets various commercial and industrial applications including dry cleaning, water heating, process heating, and air conditioning.

The keys to success of this approach are consistent product geometry and quality during manufacturing, lower capital costs, and increased reliability from a simpler trough design that reduces the potential for maintenance problems. The proposed system consists of fewer parts than conventional troughs and eliminates the need for a costly space frame support structure and concrete foundation. The researchers replaced conventional glass mirrors with a polished aluminum skin reflector attached to a polyurethane foam core to provide rigidity and structural support and accomplish cost reduction. The research team concluded that this low cost innovative reflector meets the ten year life requirement of the National Renewable Energy Lab (NREL) and, when ready for commercialization, could easily be built on a high volume production line.

As part of this project, the research team fabricated a 6 foot by 10 foot panel and formed it into a parabolic shape, measuring stress at various points on the mold throughout the process. The team found that the proposed design met structural requirements for a parabolic trough needing to sustain 25 mile per hour wind loads, 120 mile per hour wind gusts, and temperature extremes from -40°F to +140° F. This design compared in strength and durability to

conventional troughs, which use glass reflectors and space frame supports. Thermal cycling tests revealed no significant angular deformation or twisting issues.

The prototype panel was damaged during the initial trial. Because of the damage, measured efficiencies were lower than expected. To attain higher efficiencies from that model, the researchers planned to repair and optimize the reflector geometry. The thermal heat efficiency of the damaged mold varied between 30 percent and 46 percent, depending on oil fluid exit temperature. According to the research team, the concept could become feasible if the overall efficiency improved to 70 percent and manufacturing costs were significantly reduced, primarily by using castings for parts instead of machining techniques. Preliminary calculations indicated a simple payback potential of less than five years assuming the benefits of a 30 percent Federal Tax Rebate, 70 percent collection efficiency, and natural gas prices of \$9.92/MMBtu (escalating 5.7 percent per year).

Keywords: Solar, solar thermal, parabolic trough, polyurethane foam, aluminum skin, reflector, deformation

2.24.2 Introduction

The development of more cost effective distributed renewable energy resources is a key state energy goal. The goal of this project was to determine the feasibility of developing an efficient, modular, cost effective solar thermal parabolic trough system for commercial and industrial applications such as dry cleaning, water heating, process heating, and air conditioning. A successful product would enable customers to offset the use of natural gas and/or electricity consumption at their facilities.

The research team estimated that installation of 50,000 solar thermal trough systems at customer sites could reduce natural gas consumption by 19 million therms per year and lower customer energy costs by \$13 million in the first year. A single parabolic trough (6 square meter aperture) operating at 70 percent efficiency in Daggett, California, could save a commercial customer \$4,486 over the first 10 years. Including the 30 percent Federal Tax Credit increases, the 10 year aggregate savings totals \$5,687. Researchers calculated these savings based on natural gas prices at \$9.92/MMBtu, escalating 5.7 percent per year. The proposed solar trough also would qualify for carbon credits by offsetting the use of natural gas, but these credits were not included as a financial benefit.

Conventional solar troughs are generally expensive and designed for utility scale electric generation applications. Glass reflectors are typically employed on utility scale solar parabolic troughs. Utility scale units also incorporate vacuum tube heat collection elements (HCE) which are expensive and prone to breakage, leading to relatively high maintenance costs. High wind loads can deform the structure and fracture the expensive mirrors or heat collection element. Temperature change can also fracture the mirrors because of differential expansion between the support structure and the glass. Current utility scale solar trough systems require powerful hydraulic equipment to accurately track the sun. This equipment is costly as it must accurately move all the mirrors and support structure, and it requires an equally large support foundation.

This project attempted to prove that a cost effective, modular, solar parabolic trough could be developed for various applications at customer facilities. The new solar trough concept eliminates high maintenance issues with glass breakage and envisions a new manufacturing process that uses lower cost materials, which can be scaled up for volume production. The new trough design also uses a lightweight structure that requires simpler, less expensive foundation supports. The reflector is a polished aluminum sheet that is less expensive than glass and has passed National Renewable Energy Lab (NREL) testing for a 10 year life. The reflector is very similar in performance to glass with 87 percent hemispherical reflectance after five years of testing. The aluminum skin becomes a self-supporting structure when used with a polyurethane foam core. The proposed system is lightweight and employs an inexpensive gear motor to track the sun. This new solar trough has fewer components and is easier to install in the field. It is light enough for roof mounting and can process heat at temperatures up to 375° F.

The system is not intended for temperatures above 400° F so it can use air in the HCE (between the glass and metal tube). This feature can reduce maintenance issues. The center of focus is also the center of rotation, so the HCE does not move (see Figure 27). Solidly mounting the HCE means flex tubes are not required and leakage experienced in prior designs is prevented. Wind loads are minimized when the center of focus is at the center of rotation since about half the surface area is above the center of rotation and half the surface is below it. This allows use of a smaller actuator for the tracking system.

The researchers tested the proposed structure under simulated wind loading and temperature extremes. They evaluated several varieties of foam and aluminum to optimize strength and minimize cost. They fabricated and tested bar samples to derive the composite material in a parabolic trough that could sustain 25 mile an hour wind loading and 120 mile per hour wind gusts. The researchers evaluated the final trough design with finite element analysis software and molded samples to ensure the feasibility of the proposed manufacturing process.

The research team suggested the overall solar thermal efficiency could be improved to 70 percent by improving the mold process. Furthermore, the team predicted manufacturing costs could be significantly reduced by using castings for parts instead of machining techniques. If successful, these refinements could produce a viable system that could be commercialized and provide consumers with a simple payback potential of less than five years (including the benefits of a 30 percent Federal Tax Credit).

Figure 27: Heat Collection Element (HCE)



2.24.3 Objectives

The goal of this project was to determine the feasibility of a new solar thermal parabolic trough system that could be installed at a cost of \$25 per square foot and capture at least 1450 Btu per square foot per day when placed in an area with an average solar insulation rating of 7.0 kW/m² per day. The researchers established the following project objectives:

1. Verify variations in sensor accuracy, gauge repeatability, and reproducibility are less than 20 percent.
2. Create drawings and a finite element analysis (FEA) prediction table prior to testing.
3. Fabricate flat sample parts including designing and building the flat bar mold and controlling key process characteristics.
4. Verify predicted deformation matches average of test data within plus or minus 10 percent, and determine the material properties of the composite structure.
5. Document the material strength after thermal and environmental cycles and compare to initial strength.
6. Create parabolic trough drawings and a FEA prediction table to confirm the proposed parabolic design will retain its shape in 25 mile per hour winds and survive a 120 mile per hour gust.
7. Verify FEA model matches average of test data within plus or minus 10 percent.
8. Calculate rotational deformation in 25 mph wind load, and verify it is less than 0.5 degrees on the last trough in a row. It must also sustain a 120 mile per hour wind load. The trough structure must be strong enough to sustain the torsion loads that occur when a single actuator is used to control multiple parts.

9. Test the trough to verify deformation does not exceed 0.5 degrees. Evaluate the optics to confirm the tooling geometry will cause reflected light to hit the focal point. Thermal cycle the parts and retest the optics to assure that temperature change does not cause a detrimental effect.
10. Order all components for a system test and confirm that the mechanical components and the plumbing system can sustain 400° F temperatures.
11. Create efficiency equation and incident angle modifier table. Predict performance with Transys software.
12. Create production drawings of the trough assembly for cost estimates.
13. Meet a cost projection target of \$25 per square foot to achieve a five year payback in California.

2.24.4 Outcomes

1. Researchers reported the gauge repeatability and reproducibility was 5 percent of the expected deformation.
2. Researchers completed fixture drawings and deformation prediction table.
3. Researchers constructed flat bar mold and made bar samples with aluminum thickness of 0.005, 0.010, and 0.025 inches and polyurethane foam thickness of 0.5, 0.75, and 1.0 inches. They tested the foam density at 2.8, 4.0, and 8.0 pounds per cubic foot.
4. Actual foam deformation matched predicted deformation within +/- 10 percent for the three form thicknesses tested.
5. Bar samples passed over 452,000 cycles in fatigue and passed environmental and thermal testing from -40° F to 140° F without material failure. At 140° F, the trough suffered only 10 percent greater deformation than at ambient temperatures.
6. Researchers completed drawings for a 10 foot long parabolic trough body. They skipped construction of a small bench test sample for lack of time. Computational flow dynamic analysis revealed that the trough would retain its shape in 25 mile per hour winds and survive a 120 mile per hour gust.
7. FEA model predictions were very accurate, within 1 percent of actual test data.
8. Rotational deformation with 25 mile per hour wind load at the last trough on a row of 50 troughs was 0.114 degrees, much less than the desired goal of 0.5 degrees. The trough assembly easily sustained loads simulating 120 mile per hour winds and deformed .287 inches in the center and had rotational twist of 0.05 degrees.
9. The average surface deformation was 0.3 degrees. Thermal cycling revealed no angular deformation, twisting. The parabolic mold was deformed and initial geometry was not precise enough to reach thermal deformation conclusions. Before thermal cycling the reflected light did not hit the target of +/- 0.5 degrees in 47 percent of the 121 zones

which were measured. After thermal cycling the reflected light did not hit the target of ± 0.5 degrees in 43 percent of the 121 zones which were measured.

10. Researchers ordered and assembled the full prototype system.
11. The researchers did not pursue performance predictions with Transys software (with efficiency equation and incident angle modifiers) because they had not optimized the trough geometry.
12. Researchers completed initial production drawings.
13. The current design was projected to sell at a price of about \$51 per square foot based on 50,000 troughs sold per year (\$3,296 per trough). The payback period would be eight years (or five years with the Federal Tax Credit) assuming a 70 percent efficiency trough operating in Daggett, California. This concept did not meet the \$25 per square foot target, mostly due to a rapidly escalating cost of raw materials.

2.24.5 Conclusions

1. The gauge repeatability and reproducibility was excellent. The data collected by the flat bar testing was reliable and could be used to predict material properties using Finite Element Analysis (FEA).
2. The deformation model accurately predicted deformation of the polyurethane foam molds.
3. The test bars were successfully fabricated. However the mold deformed when mold pressure increased, due to overfilling. Consistent mold rigidity could be an issue during fabrication, as expanding foam pressure could change the shape of the parabolic trough. An alternative manufacturing process is needed to correct this problem.
4. Researchers met this objective. The study developed a reliable method of predicting stress and deformation on the composite structure.
5. The foam bars met all requirements for thermal, fatigue, and environmental testing.
6. Researchers produced parabolic trough drawings, along with a three dimensional model. FEA indicated that the design would retain its design shape within acceptable limits during a 25 mile per hour wind loading and 120 mile per hour wind gust without failing.
7. The FEA model used for deformation can be assumed to be valid since predicted performance was within 1 percent of actual test data.
8. Rotational deformation of a row of troughs was acceptable for 25 mile per hour wind loading and a 120 mile per hour wind gust. Multiple lockout devices are needed to anchor a row of troughs rather than relying on a single actuator.
9. Mold geometry was deformed and not perfectly parabolic. Thus 47 percent of the reflected rays were outside the 0.5 degree window. Better mold fabrication techniques

would improve mold geometry and enable a greater percentage of reflected rays on the focal point, thus increasing the overall thermal efficiency of the trough.

10. Researchers assembled the heat collection element, tracking controller, and bench prototype system. The trough rotated smoothly, but the tracking system was erratic and failed. An improved tracking system is necessary for the best heat collection possible.
11. Researchers collected data to predict thermal performance of the trough based on manual calculations. Low trough thermal efficiency (46 percent at 185° F exit oil temperature) was mostly due to parabolic mold geometry problems and the need to manually track the sun during the test. There was not enough time and money to fabricate a better parabolic trough and tracking system to improve trough solar thermal efficiency. Therefore researchers decided not to purchase the Transys software for more accurate performance predictions.
12. Researchers completed production drawings for the bench prototype system. However design changes are needed and the use of molded parts (instead of machine milled parts) is required to decrease system cost and improve quality.
13. Although the design did not meet the \$25 per square foot price goal, a five year payback is still possible with the inclusion of the 30 percent Federal Tax Credit, assuming that system thermal efficiency can reach 70 percent. The researchers should conduct concurrent engineering and manufacturing design both to lower manufacturing cost and to reduce the sensitivity of their design to the cost of raw materials.

Despite time and funding limitations, the researchers were able to partially demonstrate the feasibility of a practical, cost effective, modular solar parabolic trough concept for commercial and industrial applications. This project led to a sound method of predicting structural performance of a lightweight composite trough. It proved that the foam composite retains strength after temperature extremes and fatigue cycles. It proved the process is viable even when the foam expands to the full length of 10 feet. However there are key hurdles which need to be addressed before such a system can achieve commercial viability. For instance, a new manufacturing process needs to be developed that ensures consistent geometry of the modular troughs with minimal risk of deformation during the foam filling process. Secondly, additional work is needed to optimize the foam density so that it can withstand stresses during the molding process without deforming the parabolic trough. Thirdly, various parts need to be cast in lieu of machining techniques. Finally, a cost effective solar tracking device needs to be developed or outsourced to another supplier to ensure optimal capture and focus of the sun's reflective rays and improve thermal efficiency to target levels.

2.24.6 Recommendations

The proposed modular solar parabolic trough system has potential but needs additional development work to fully determine system viability. This includes design and manufacturing improvements, mold material optimization, reduction in material costs, cost effective automated solar tracking system, and more extensive product durability and field testing. The research team should consult with third party fabricators who specialize in foam composite

materials in an effort to enhance the fabrication process, optimize design geometry, and manage mold deformation issues. Suppliers should be consulted on ways to reduce the cost of parts and materials. The research team should also consider using an outside supplier for the solar tracking system unless a superior, less expensive design is possible. The proposed low cost trough needs extensive durability and field testing to ensure performance and reliability. A market and competitive analysis is needed to ensure that this product has broad potential and that it can be well positioned in the marketplace.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.24.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of energy in California.

This low cost parabolic trough compares favorably to other renewable energy devices in terms of \$/kW produced (thermal or electric). There are roughly 480,000 commercial and industrial natural gas customers in California according to the U.S. Energy Information Administration. Assuming that approximately 10 percent of these customers have adequate heating requirements for the new solar parabolic trough, the full market potential in California is about 48,000 customers. Further assuming that this new solar thermal trough concept would capture at most 10 percent of the California market potential, about 4,800 customers could benefit. Of course, the U.S. and global market potential would be an order of magnitude greater than the California market. Using figures from the research team, sales of 4,800 systems in California could reduce natural gas consumption by 1.8 million therms per year and lower customer energy costs by \$1.2 million in the first year. A single parabolic trough (6 square meter aperture) operating at 70 percent efficiency in Daggett, California, could save a commercial customer a total of \$4,486 over the first 10 years. Including the 30 percent Federal Tax Credit increases the 10 year aggregate savings to \$5,687. Calculations are based on natural gas prices at

\$9.92/MMBtu, escalating 5.7 percent per year. The proposed solar trough could also qualify for carbon credits by offsetting the use of natural gas if and when a carbon trading market materializes.

2.24.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.24.8.1 Marketing/Connection to the Market

This low cost parabolic trough compares favorably to other renewable energy devices in terms of \$/kW produced (thermal or electric). This device could be valuable to customers because it can provide heat at temperatures not attainable by current flat plate collectors. A company in India has expressed interest in helping to market this technology/product.

2.24.8.2 Engineering/Technical

The research team plans further development work on a part-time basis. It will pursue the use of parts made from castings instead of machining techniques to reduce costs. The research team plans to explore various ways to improve manufacturing, increase system thermal efficiency, and lower costs for this product to be competitive in the marketplace.

2.24.8.3 Legal/Contractual

The research team has submitted and received a provisional patent for the trough concept.

2.24.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

The research team will be pursuing UL certification for the parabolic trough concept. The polyurethane foam can be carcinogenic. Therefore the foam must be molded in a factory with proper safety measures in place.

2.24.8.5 Production Readiness/Commercialization

The concept is not yet sufficiently developed for commercialization.

2.25 Production of Syngas from Dairy Manure to Replace Natural Gas

Awardee: University of Arkansas Division of Agriculture
Department of Biological & Agricultural Engineering

Principal Investigators: Samy Sadaka

2.25.1 Abstract

This study explored the feasibility of a multi-stage biofuels process that could produce medium heat value gas from a mixture of dairy manure and wheat straw suitable for on-site power generation or injection into the natural gas pipeline system. If successful, this concept could help California reduce greenhouse gas emissions (GHG) and achieve its renewable energy goals.

The multi-stage process involved three distinct steps: biodrying, gasification, and gas conditioning. First, researchers demonstrated how biodrying could be a potential replacement for conventional liquid manure storage practices by blowing air (forced aeration) into a storage vessel containing dairy manure and wheat straw.

After drying, researchers placed the dried mixture into a gasification system and produced synthetic gas. They conducted three air gasification trials under different equivalence ratios⁵⁴ (0.25, 0.30, and 0.35) followed by various air steam gasification experiments. Researchers noted that increasing the steam flow rate raised hydrogen concentration levels and lowered carbon monoxide levels without any material change in gas heating value.

Finally, researchers conditioned the producer gas by using a steam reformer and a carbon dioxide capture technique which significantly enhanced the heating value of the gas from the gasification unit and produced a gas product that could be injected into the natural gas pipeline system.

Researchers estimated that this concept has the potential of reducing the use of natural gas in California by approximately six billion cubic feet per year and that the value of the biogas produced by this process has a market value of \$24 million per year, assuming a natural gas market price of \$4 per million British Thermal Units (Btu). In addition, researchers calculated that the market value of the biogas from a typical farm with 1,000 cows was approximately \$664,300 per year. A reduction in natural gas use would also decrease carbon dioxide emissions by 412,000 tons per year, assuming that the biodried mixture had a net zero impact on the environment.

Keywords: Dairy manure, wheat straw, biodrying, gasification, steam reformer

⁵⁴ Equivalence ratio of a system is defined as the ratio of the fuel-to-oxidizer ratio to the stoichiometric fuel-to-oxidizer ratio.

2.25.2 Introduction

Dairy manure production in California exceeds 1.5 million tons/year (dry basis). The potential renewable energy that could be captured from this harvestable manure is approximately 2.7×10^{16} joule of heat energy, an amount that exceeds the annual energy consumption of approximately one million single family households in California. Furthermore, the production of wheat straw in California is 400,000 tons/year with an equivalent heat energy potential of 7×10^{15} joule.

This study explored the feasibility of a multi-stage biofuels process that could produce medium heat value gas from a mixture of dairy manure and wheat straw, suitable for on-site power generation or injection into the natural gas pipeline system. If successful, this concept could help California reduce greenhouse gas emissions (GHG) and achieve its renewable energy goals.

The multi-stage process involved three distinct steps: biodrying, gasification, and gas conditioning.

The major constraint that limits conversion of manure to synthetic gas using thermo-chemical processes is its high moisture content. The American Society of Agricultural and Biological Engineers (ASABE) stated that moisture contents of fresh dairy and beef manures are roughly 88 percent and 92 percent (dry basis), respectively. Energy consumption to remove moisture from dairy manure through conventional methods is normally higher than the energy gain by dried manure. One possible way to reduce manure moisture content in a cost effective manner is biodrying.

Biodrying is an emerging treatment that is designed to reduce moisture in biological waste products without the need for an external heat source. The heat required for drying is generated by the aerobic microorganisms already present in the biological waste itself. The availability of necessary nutrients and aerobic conditions facilitates metabolic activities, resulting in elevated temperatures. Implementation of biodrying on high moisture waste like manure requires separation of solids and the addition of an amendment (wheat straw) which can reduce moisture levels to 60 to 70 percent (wet basis). Wheat and rice straw amendments are abundant in California and considered to be an underutilized waste stream. The proposed biodrying process could significantly reduce energy requirements needed to completely dry the manure and thus could have great potential for California ratepayers in creating a new renewable resource.

Use of heat from composting to evaporate water and dry compost has been used in municipal systems for some time.⁵⁵ Biodrying has been shown to work on animal wastes in the past.⁵⁶

However the in-vessel machinery was seen as too expensive to run on a dairy farm.

55 Haug, R. T., 1994 Composting Process Design Criteria. Part I – IV.

56 Richard, T.L., and H. L. Choi, 1996 Optimizing the Composting Process for Moisture Removal: Theoretical Analysis and Experimental Results. *ASAE Meeting Paper No. 964014*.

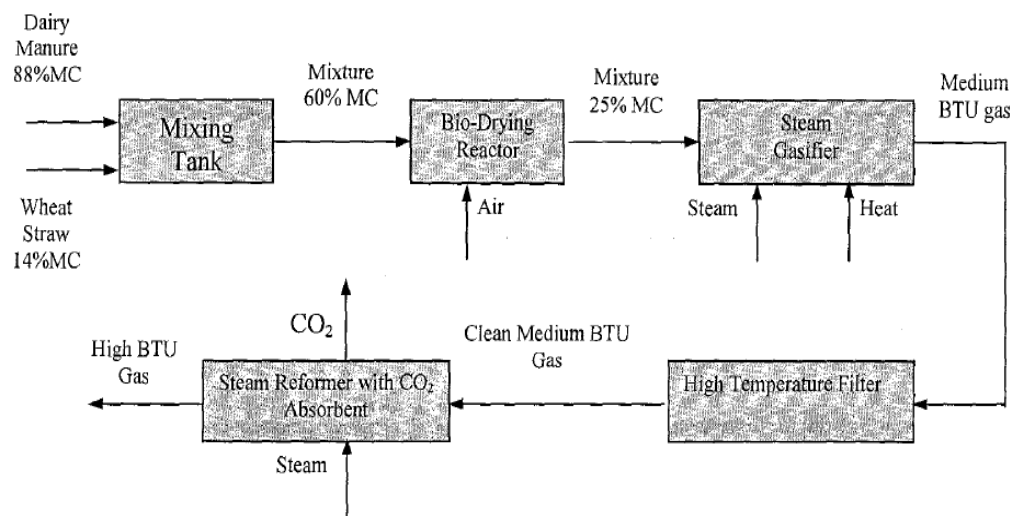
The research team in this project investigated the effects of blowing air (forced aeration) into a mixing tank containing dairy manure and wheat straw. The combination of heat generated from aerobic decomposition and forced aeration resulted in significant moisture reduction of the manure. Moisture was reduced from 60 percent to 25 percent within the first three weeks of testing. Researchers also observed reductions in odor, volume, weight, and pathogens. The research team determined that biodrying could be a potential replacement for conventional liquid manure storage practices that have suffered from high cost, leakage, and odor issues.

After drying, the researchers placed the dried mixture in a gasification system and produced synthetic gas. Resulting gas yield and higher heating value ranged between 1.61 to 1.74 cubic meter/kilogram (of biomass) and 4.55 to 4.86 mega joule per cubic meter (122–130 Btu per cubic foot) with the highest yield and heating value occurring under an equivalence ratio of 0.25. Values of cold gas efficiency ranged from 64.17 percent to 65.38 percent. In addition, the researchers investigated three air steam gasification experiments of biodried manure. They found that increasing the steam flow rate from 0.04 to 0.06 kilogram/minute raised hydrogen concentration levels from 6.21 percent to 8.47 percent and lowered carbon monoxide levels from 14.84 percent to 11.12 percent. The gas heating value did not increase significantly. The steam gasification process converts the carbon containing material into a synthetic gas (syngas), which is composed primarily of carbon monoxide and hydrogen. Syngas can be used as a fuel to replace natural gas or can be used as a basic chemical building block for a large number of processes in the petrochemical and refining industries.

Researchers then conditioned the syngas by using a steam reformer and carbon dioxide capture technique that significantly enhanced the heating value of the gas by 32.5 percent. High temperature filtration also decreased the particulate concentration in the producer gas from 480 milligram/cubic meter to 80 milligram/cubic meter.

Figure 28 is a flow chart that describes the multi-stage process, including biodrying, gasification, and gas conditioning.

Figure 28: Flow Chart of the Proposed Dairy Manure–Wheat Straw to Medium Btu Gas



Researchers estimated that this concept has the potential of reducing the use of natural gas in California by approximately six billion cubic feet per year (equivalent to 0.26 percent of total natural gas consumption in California), assuming that 50 percent of dairy cow manure (750,000 tons/year) produced in California could be utilized via this technique. Researchers estimated the market value of this biogas to be \$24 million per year (assuming a natural gas market price of \$4 per million Btu) and that carbon dioxide emissions from natural gas could be reduced by 412,000 tons per year (assuming that the biodried mixture has a net zero impact on the environment). Finally, researchers calculated that the market value of the biogas from a typical farm with 1,000 cows was approximately \$664,300 per year.

2.25.3 Objectives

The goal of this project was to prove the feasibility of a multi-stage biofuels process that could produce medium heat value gas from a mixture of dairy manure and wheat straw suitable for either on-site power generation or injection into the natural gas pipeline system. The researchers established the following project objectives:

1. Produce biodried dairy manure containing less than 25 percent moisture content. Observe the effects of wheat straw to manure ratio and airflow rate on moisture content.
2. Produce gas stream from gasification process with a medium heat content of about 165 Btu per cubic foot. Evaluate the effects of bed temperature and biomass to steam ratio.
3. Produce gas with less than 10×10^{-6} pound per cubic foot (160 milligram per cubic meter) of particulate concentration.
4. Run several experiments to test steam reforming of producer gas. Evaluate factors to maximize gas heat content.

5. Perform mass and energy balances on each individual system as well as the overall system with a precision of up to +/- 5 percent.
6. Develop an economic evaluation based on 1,000 cows as a guide for California dairy producers.

2.25.4 Outcomes

1. Average moisture decreased as expected in all reactors with varying degrees. Maximum reduction occurred under high aeration, with moisture content decreasing from 56.9 percent to 27.9 percent. Medium and low aeration reactors reduced moisture content to 34.5 percent and 34.6 percent, respectively.
2. Gas heating value reached 4.86 mega joule/cubic meter (130 Btu per cubic foot), 5.60 mega joule/cubic meter (150 Btu per cubic foot), and 6.20 mega joule/cubic meter (166 Btu per cubic foot), after air steam gasification, steam reformation, and carbon dioxide capture, respectively. Both steam reformation and carbon dioxide capture processes resulted in increased hydrogen concentration and decreased carbon monoxide concentration. Test results indicated that potassium carbonate and sodium carbonate were able to capture most, but not all, of the carbon dioxide from the producer gas.
3. Researchers produced gas at approximately 5×10^{-6} pound/cubic foot (80 milligram/cubic meter), exceeding the objective.
4. Researchers found that increasing the steam flow rate from 0.04 to 0.06 kilogram per minute led to an increase in hydrogen concentration from 6.2 percent to 8.5 percent while carbon monoxide concentration decreased from 14.8 percent to 11.1 percent. Heating value of the producer gas did not change significantly.
5. Researchers were only able to perform a mass and energy balance on the gasification system. At an equivalence ratio of 0.25, the input biomass and air measured 59.1 kilograms per hour. The output gas and char measured 48.9 kilograms per hour. The mass balance was achieved by attributing the difference of 10.2 kilograms per hour to tar and water content in the producer gas. Researchers found energy value of the input feedstock to be 75.9 kilowatts. The output energy value was 58.7 kilowatts. The energy balance was achieved by attributing the difference of 17.2 kilowatts to tar and water content in the producer gas.
6. Researchers assumed that a typical farm has about 1,000 cows with a manure moisture content of 70 percent. They also assumed that approximately 21,980 kilograms of bulking material (e.g., wheat straw) with a moisture content of 10 percent would be needed. The daily biodried dairy manure-straw mixture would be 51,616 kilograms with moisture content of about 27 percent. This material would then be converted to producer gas with a heat value of 480,000 mega joule (455 million Btu). Therefore it could replace about 12,000 cubic meters (or about 420,000 cubic feet) of natural gas per day. The market value of the displaced gas for a typical farm with 1,000 cows would, therefore, be approximately \$664,300 per year at a market price of \$4 per million Btu.

2.25.5 Conclusions

1. The targeted decrease in moisture content was met only under high aeration conditions. Low and medium aeration fell short of the target.
2. Researchers successfully demonstrated biodrying, gasification, and gas conditioning technologies to produce medium heating value producer gas from wet manure mixed with wheat straw.
3. Conventional filtering techniques were very effective in meeting and exceeding the goal of reducing particulates by a factor of two.
4. Increasing steam flow in the reformer raised hydrogen concentration levels and lowered carbon monoxide concentration levels without changing the heating value of the producer gas.
5. Researchers obtained mass and energy balance for the gasification system by attributing the difference between input and output to tar and water content in the producer gas. Future research is needed to verify this assumption and to complete the mass and energy balance for the steam reformer and carbon capture components.
6. It is not yet clear that this process is more cost effective than conventional manure disposal and other biogas production techniques.

Researchers were able to successfully demonstrate a multi-stage process using biodrying, gasification, and gas conditioning that could produce medium heat value gas from a mixture of dairy manure and wheat straw. Additional work is needed to optimize system performance and determine whether this concept is cost effective compared to other renewable technologies and manure cleaning techniques.

2.25.6 Recommendations

The proposed concept has potential but needs additional development work to determine fully the system viability and commercial potential, including:

1. Continuous straw feeding and biodrying system in lieu of batch processing
2. A modular gasification unit that is appropriately sized for the biodrying system
3. Continuous cleaning of the filtration system
4. An effective feedstock storage system

In addition, the researchers need to estimate system cost and determine the economic feasibility of the proposed process system compared to other alternatives. Researchers should also verify that the gas produced by the system can indeed meet the very stringent natural gas pipeline quality standards. Finally, researchers need to verify that the biodried gas can be considered to have a net zero greenhouse gas emissions impact to the environment.

The research team should continue to explore partnership opportunities with other companies to accelerate development and commercialization of this concept. It also needs to conduct a patent search to ensure that this work does not infringe on existing intellectual property.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.25.6 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply, transmission, or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California energy supply and distribution system. This concept has the potential of reducing the use of natural gas in California by approximately six billion cubic feet per year (equivalent to 0.265 of total natural gas consumption in California), assuming that 50 percent of dairy cow manure (750,000 tons per year) produced in California could be utilized by this process. This would enable the reduction of carbon dioxide emissions by 412,000 tons/year, assuming that the feedstock is found to have a net zero impact on greenhouse gas emissions. The market value of the biogas produced by this process is estimated to be \$24 million per year (assuming a natural gas market price of \$4 per million Btu). The market value of natural gas that could be displaced by a typical farm with 1,000 cows is approximately \$664,300 per year.

2.25.6.1 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researches' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.25.6.2 Marketing/Connection to the Market

Market players are dairy farmers, utility companies, and equipment suppliers.

2.25.6.3 Engineering/Technical

The research team appears to recognize that there are several technical hurdles remaining before this concept can be viable. In the future researchers plan to test longer term duration of the catalyst used in the steam reformer.

2.25.6.4 Legal/Contractual

The researchers have not applied for any patents.

2.25.6.5 Environmental, Safety, Risk Assessments/ Quality Plans

The researchers claimed they found no environmental, safety, or other risks. They provided no supporting data for this claim.

2.25.6.6 Production Readiness/Commercialization

The concept is not yet sufficiently developed for commercialization.